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AUTOMATION STUDY: SATELLITE
SERVICING (TRW Systems Group)
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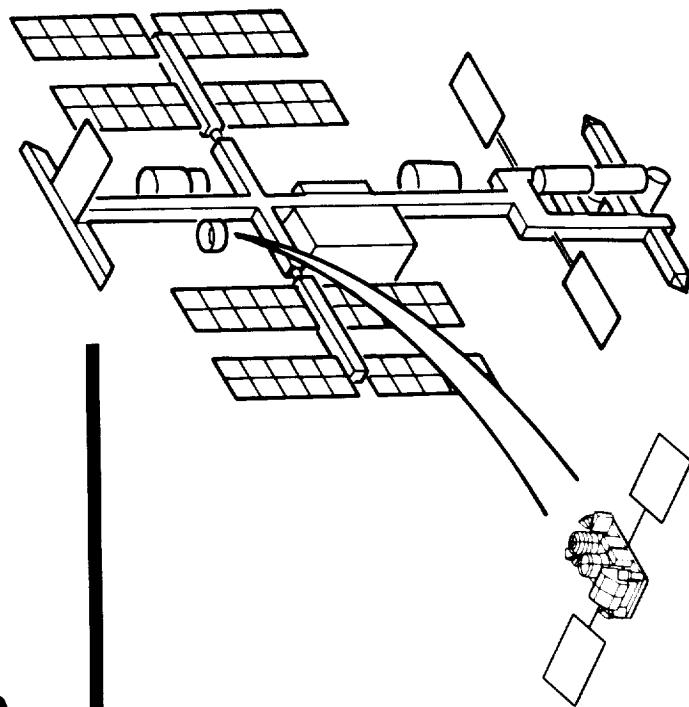
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Space Station Automation Study – Satellite Servicing

Contract NAS8-35081

Final Briefing at
NASA/Johnson Space Center
Houston, Texas
27-28 Nov. 1984





Federal Systems
Division
TRW Space &
Technology Group

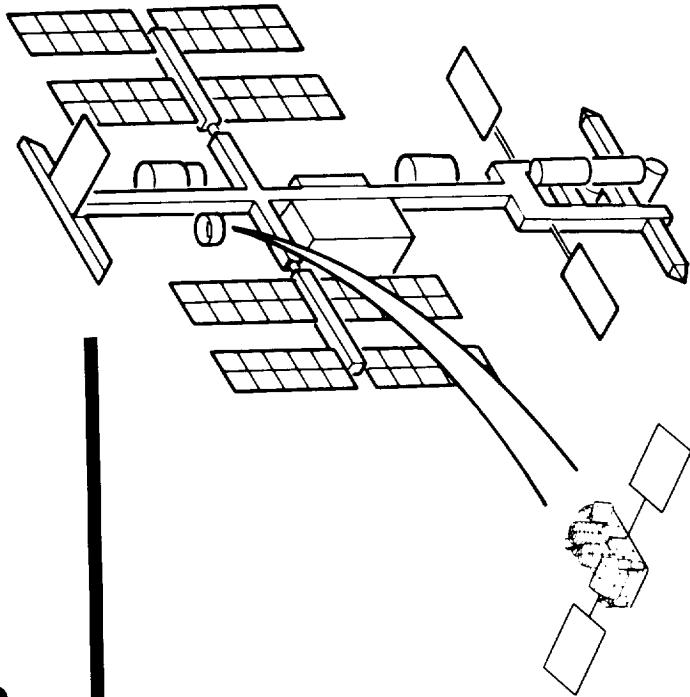


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PREFACE

The Space Station Automation Study - Satellite Servicing - Final Review was held at the NASA Lyndon B. Johnson Space Center, Houston, Texas on 27-28 November 1984.

This document, generated in accordance with our contractual requirements for study reporting, contains the presentation material prepared by the TRW Space and Technology Group for this Final Review.

The technical work of this six-month study is complete. The study was started in early June and was completed in late November 1984. The final report is in preparation; the Executive Summary was submitted to NASA at this review. The final report, Technical Volume, will be submitted in early December 1984. This study, to define the technology requirements for automated satellite servicing operations on board the NASA Space Station, is one of several parallel studies performed by a team of NASA contractors addressing various facets of Space Station Automation. The other contractors are Hughes Aircraft, General Electric, Martin Marietta, Boeing Aerospace, SRI International, and the California Institute at the University of California, San Diego.

The TRW study manager was Mr. Hans Meissinger. Requests for information on this review should be directed to him at (213) 536-2996.

TRW acknowledges the excellent direction provided us on this study by Dr. Victor Anselmo, NASA Headquarters (Code S) and Mr. Jon Haussler, NASA/Marshall Space Flight Center (Code PMU1).



PRESENTATION TOPICS

1. INTRODUCTION AND STUDY HIGHLIGHTS
 2. STUDY RESULTS
 - TASK 1 AUTOMATED SERVICING REQUIREMENTS
 - TASK 2 AUTOMATED SERVICING TECHNOLOGY ASSESSMENT
 - TASK 3 SPACE STATION SERVICING FACILITY CONCEPTS
 3. AUTOMATED SERVICING TECHNOLOGY PRIORITIES AND EVOLUTION
 4. SPACECRAFT DESIGN APPROACHES FOR SERVICING
 5. AUTOMATION TECHNOLOGY TRANSFER TO EARTH-BASED APPLICATIONS
 6. CONCLUSIONS, RECOMMENDATIONS AND SUMMARY
- GENERAL DISCUSSION

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INTRODUCTION

DEFINITIONS

AUTONOMY: The ability to function as an independent unit or element, over an extended period of time, performing a variety of actions necessary to achieve pre-designated objectives, while responding to stimuli produced by integrally-contained sensors.

AUTOMATION: Automation is the use of machines to effect initiation, control, modification, or termination of system/subsystem processes in a predefined or modeled set of circumstances. The implication is that little or no further human intervention is needed in performing the operation. The terms hard automation and flexible automation define subsets of automation.

TELEOPERATION ("REMOTE OPERATION"): Use of remotely controlled sensors and actuators allowing a human to operate equipment even though the human presence is removed from the work site. Refers to controlling the motion of a complex piece of equipment such as a mechanical arm, rather than simply turning a device on or off from a distance. The human is provided with some information feedback (visual display or voice) that enables him to safely and effectively operate the equipment by remote control.

AUGMENTED TELEOPERATOR: A teleoperator with sensing and computation capability that can carry out portions of a desired operation without requiring detailed operator control. The terms "teleautomation" and "tele-robotics" have been used here.

TELEPRESENCE ("REMOTE PRESENCE"): The ability to transfer a human's sensory perceptions, e.g., visual, tactile, to a remote site for the purpose of improved teleoperation performance. At the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions. At the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite.

ROBOT: A generic term, connoting many of the following ideas: A mechanism capable of manipulation of objects and/or movement having enough internal control, sensing, and computer analysis so as to carry out a more or less sophisticated task. The term usually connotes a certain degree of autonomy, and an ability to react appropriately to changing conditions in its environment. Robotics is a specialized discipline within the broader fields of autonomy and automation.

ARTIFICIAL INTELLIGENCE: That branch of computer science concerned with the design and implementation of programs which make complicated decisions, learn or become more adept at making decisions, interact with humans in a way natural to humans, and in general, behave in a manner typically considered the mark of intelligence.

EXPERT SYSTEM: An expert or knowledge-based system is one that stores, processes, and utilizes a significant amount of information about a particular domain of knowledge to solve problems or answer questions pertaining to that domain. The system is able to perform at the level of an experienced human practitioner working in that domain of knowledge.

LIST OF ABBREVIATIONS AND ACRONYMS

AFSD	U.S. Air Force Space Division	LEO	Low Earth Orbit
AI	Artificial Intelligence	MM	Martin Marietta Aerospace Company
CCTV	Closed Circuit Television	MIT	Massachusetts Institute of Technology
COR	Contracting Officer's Representative	MMS	Multi-Mission Modular Spacecraft
CSI	California Space Institute	MMU	Manned Maneuvering Unit
DoD	U.S. Department of Defense	MPF	Materials Processing Facility (Free Flying)
DS	(Space Station) Data System	MSFC	Marshall Space Flight Center
EVA	Extra-Vehicular Activity	NASA	National Aeronautics & Space Administration
FSS	Flight Support System	OMV	Orbital Maneuvering Vehicle
GE	General Electric Company	ORU	Orbital Replacement Unit
GEO	Geosynchronous Earth Orbit	OTV	Orbital Transfer Vehicle
GM	General Motors, Inc.	PFR	Portable Foot Restraint
GRO	Gamma Ray Observatory	RMS	Remote Manipulator System
GSFC	Goddard Space Flight Center	S/C	Spacecraft
HO	Human Operator	SS	Space Station
HQ	NASA Headquarters	SMM	Solar Maximum Mission (Spacecraft)
IOC	Initial Operational Capability	STS	Space Transportation System (Shuttle)
IR&D	Independent Research and Development	T/M	Telemetry
IVA	Intra-Vehicular Activity	T/O	Teleoperator
JSC	Johnson Space Center	VHSIC	Very High Speed Integrated Circuits



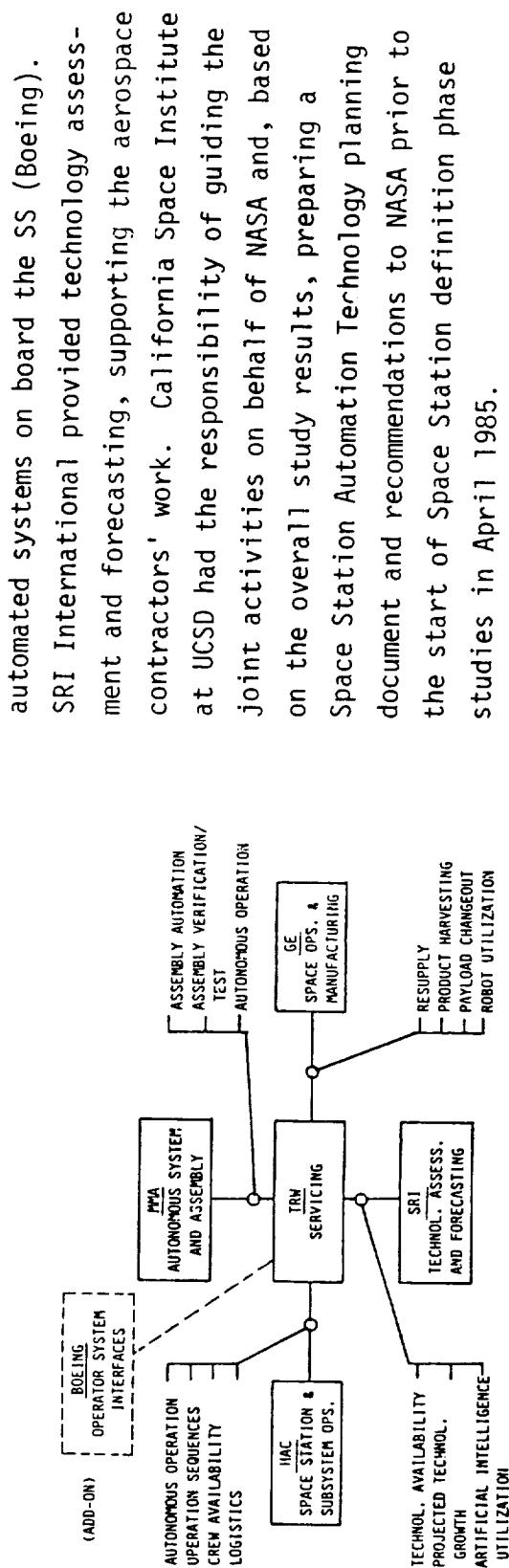
1. INTRODUCTION AND STUDY HIGHLIGHTS
 - GENERAL INFORMATION
 - STUDY OBJECTIVES
 - STUDY SCHEDULE

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TRW STUDY OBJECTIVES

Our study focused on the role of automation technology and its utilization in support of on-orbit servicing of satellites. The servicing modes considered included servicing on board the Space Station and "in-situ", i.e., remote from the Station. A concept for a generic servicing facility was defined, and the evolution of servicing capabilities and of available technology along with Space Station growth was taken into consideration.

Concurrent studies by other NASA aerospace contractors addressed a variety of Space Station automation concerns including 1) Space Station and subsystem operation autonomous from ground control (Hughes Aircraft), 2) automated manufacturing (General Electric), 3) automated assembly of large structures (Martin Marietta), and 4) human operator interfaces with automated systems on board the SS (Boeing).



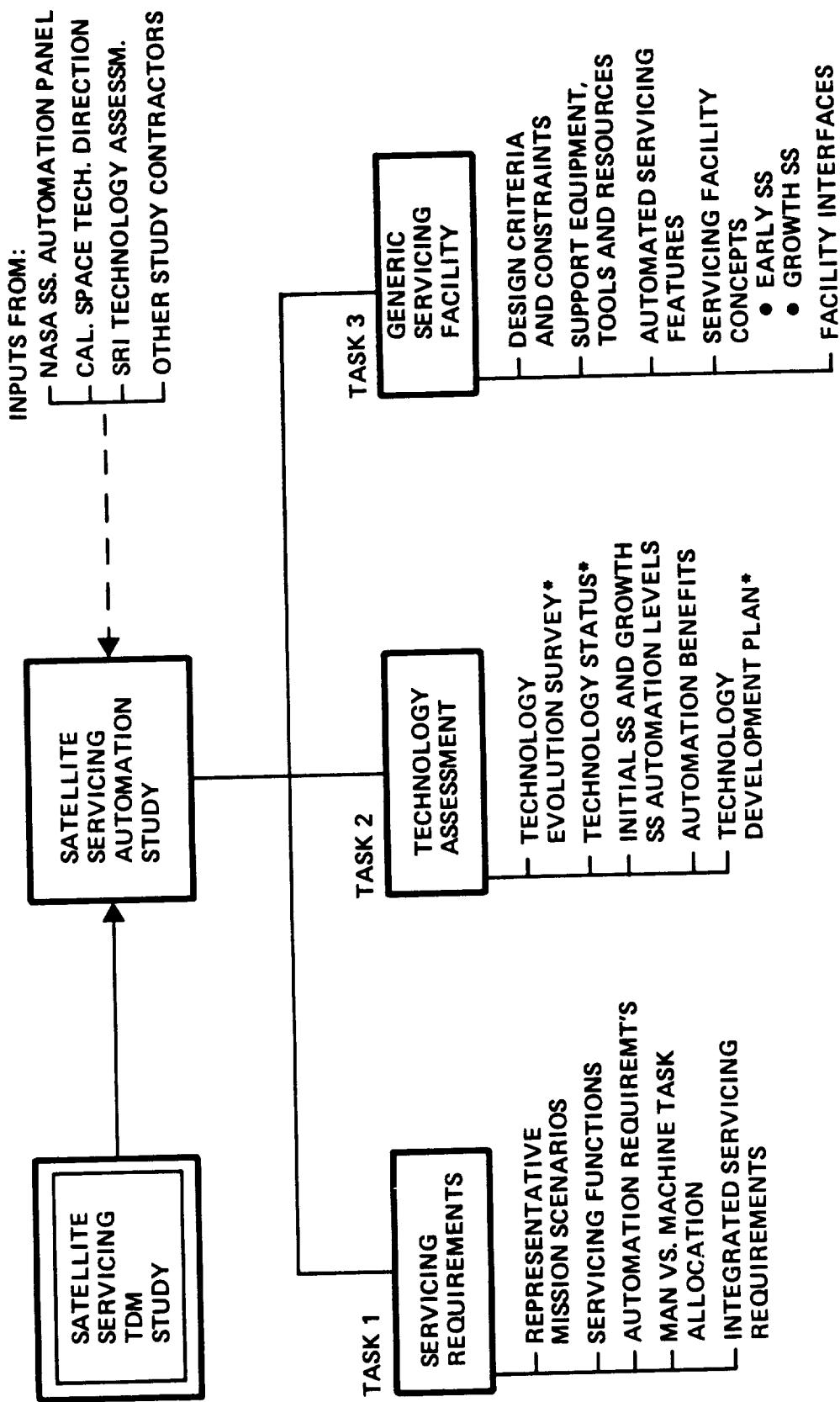
- ANALYZE CURRENT AND POTENTIAL CAPABILITIES OF AUTOMATION TECHNOLOGY FOR UTILIZATION IN SPACE.
- DETERMINE ROLE OF AUTOMATION IN SERVICING OF SATELLITES AND SPACE STATION SUBSYSTEMS/PAYLOADS.
- DEFINE GENERIC SERVICING FACILITY CONCEPT WITH AUTOMATED CREW SUPPORT FEATURES FOR EARLY SPACE STATION.
- PROJECT AUTOMATED SERVICING TECHNOLOGY EVOLUTION AND ITS ACCOMMODATION ON GROWTH SPACE STATION.

AUTOMATION STUDY TASK BREAKDOWN

The chart shows the breakdown into three study tasks: 1) servicing requirements, 2) technology assessment, and 3) generic servicing facility concepts, as well as their respective subtasks.

The study was performed as an add-on to the earlier study of Technology Development Missions (TDM) for Satellite Servicing on the early Space Station. The study period extended from June through November 1984 (see schedule on next chart). We drew on technical data obtained as a result of the TDM study as well as on inputs received from parallel studies of other aerospace contractors and from SRI International. The technical direction of the study came from NASA HQ and MSFC as well as from California Space Institute which had the task of coordinating the efforts of the team of all study participants.

Automation Study Task Breakdown



*SUPPORTED BY SRI DATA AND CONSULTATION

TASK ELEMENTS AND SCHEDULE

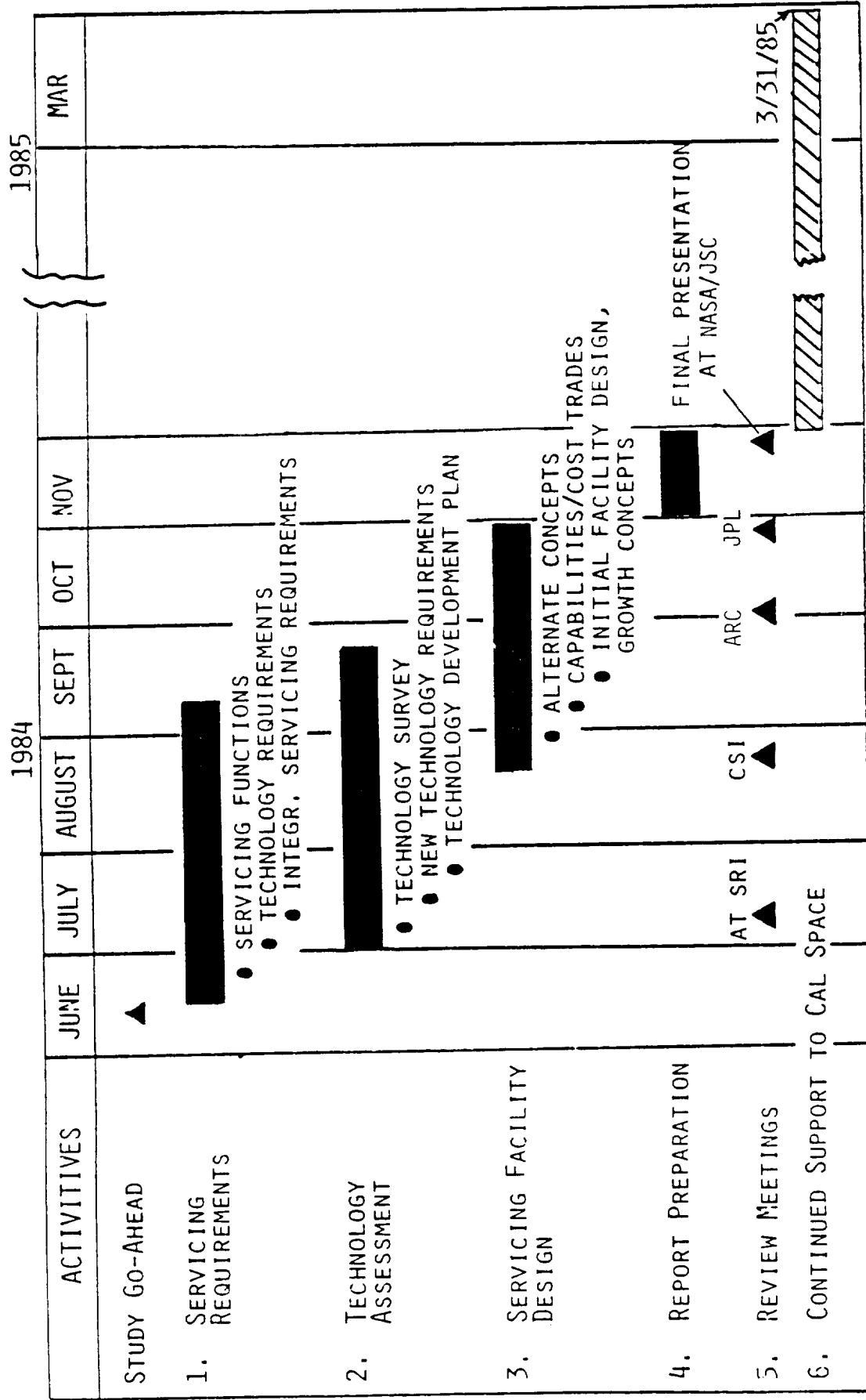
The schedule shows the time phasing of the three study tasks and their subtasks in the period from June through October 1984. The nature of the technical effort called for a substantial overlap of the time periods involved, primarily because information was flowing back and forth between the related efforts.

The last month (November) was set aside for study documentation. There were frequent interim review meetings, approximately one month apart, during the study activity. Each review meeting required a substantial amount of documentation, with data flowing to SRI and California Space Institute for the purpose of close interaction with study participants.

A continued low level support effort in the time from December 1984 through March 1985 is envisioned to assist California Space Institute and NASA in their integrated report preparation activities.

TASK ELEMENTS AND SCHEDULE

TRW



SATELLITE SERVICING ISSUES

On the basis of TRW's earlier related satellite servicing studies, we have identified seven issues of principal importance which are listed on the facing chart. Of these, the first four, namely, safety, project and operations costs, and space system design for servicing compatibility are of primary concern. The three remaining issues, technology readiness, space station evolution and user acceptance are equal in relative priority.

SAATELLITE SERVICING ISSUES

SEVEN ISSUES DOMINATE ON-ORBIT SATELLITE SERVICING:

1. SAFETY
2. PROJECT COSTS
3. OPERATIONS COSTS
4. SPACE SYSTEMS DESIGNED FOR SERVICING
5. TECHNOLOGY READINESS
6. SPACE STATION EVOLUTION
7. USER ACCEPTANCE



MAN-MACHINE PARTITIONING CONSIDERATIONS

One of the major objectives of the study was to determine effective combinations of the strongest capabilities of automated functions and of man's functions in performing satellite servicing tasks. The chart lists principal criteria of the strength of machine operations versus human operations. The automated system is capable of performing repetitive operations under predictable conditions and is utilized most effectively where it enhances true productivity and safety (e.g., by tasks which would otherwise require EVA). Man's unique cognitive sensing and manipulative skills and his ability to react to unforeseen situations were the criteria for assigning certain tasks to the crew rather than the automated system. Related experience on Shuttle missions in 1984 highlights this fact: 1) the retrieval and repair by astronauts of the Solar Max Mission (SMM) spacecraft in April 1984 and the recovery of two communications satellites, Palapa and Westar in November 1984.

Related questions addressed by the study include the following: What type of automation or robotics is needed and how will it be used? How much does automation facilitate crew tasks and enhance productivity? How much time saving is achieved? What is the impact on operational safety and what satellite design, standardization and operational requirements are imposed by automated servicing?

Subsequent discussion in this briefing will take issue with these important questions.



MACHINE CRITERIA

- TIME CRITICAL
- REPETITIVE/PREDICTABLE
- PRECISION
- PRODUCTIVITY ENHANCEMENT
- SAFETY ENHANCEMENT
- REMOTE LOCATION

MAN CRITERIA

- TIME EFFECTIVENESS
- UNPREDICTABLE
- MOTOR SKILLS
- COGNITIVE ABILITY
- PATTERN RECOGNITION
- SEQUENCING COMPLEXITY

STUDY HIGHLIGHTS

This chart presents four categories of study highlights.

Emphasis - The TRW study concentrated on satellite and Space Station servicing requirements, technology, and facilities as they relate to automation equipment and operations. We used the reference mission case-study approach to derive information on these three topics. Four representative reference mission scenarios were defined which cover a wide spectrum of space-based servicing functions, with the Space Station as host vehicle.

Role of Automation - The study established the useful role of automation in expanding the scope of space-based servicing. Teleoperation predominates in early missions, while robotics and AI support requirements increase in later missions as the technology evolves. Comprehensive Space Station data system support is essential in all of the missions investigated. The results obtained show that there is a high degree of commonality in automation requirements across the mission spectrum, with favorable implications on cost economy of the technology development.

Impact on Space Station - Servicing in general and automated servicing, in particular, significantly affects Space Station design, facilities arrangement, resource requirements and operations (ground and space), and the role, size and skills of the Station's crew.

Benefits - Automated space-based servicing will capitalize on Earth-based automation technology.

In turn, automation technology developments for space-based servicing can benefit terrestrial applications within the U.S. industry.



EMPHASIS

TRW EFFORT CONCENTRATED ON SERVICING:

- SYSTEMS LEVEL REQUIREMENTS
- TECHNOLOGY ASSESSMENTS
- SPACE STATION FACILITIES CONCEPTS

USEFUL ROLE OF AUTOMATION IN SERVICING

- TELEOPERATIONS APPLICATIONS
- ROBOTIC TECHNIQUES
- DATA SYSTEMS TO SUPPORT SERVICING
- GROWTH TO INCREASING CAPABILITY
- SUPPORT EQUIPMENT COMMONALITY

MAJOR IMPACT ON SPACE STATION:

- ARCHITECTURE AND CONFIGURATION
- OPERATIONS, SPACE AND GROUND
- USE OF THE CREW

AUTOMATION OFFERS MEASURABLE BENEFITS TO:

- IN-SPACE SERVICING OPERATIONS
- GROUND BASED INDUSTRIAL APPLICATIONS
- THROUGH TECHNOLOGY SPIN-OFF





2. STUDY RESULTS

TASK 1 AUTOMATED SERVICING REQUIREMENTS

TASK 2 AUTOMATED SERVICING TECHNOLOGY ASSESSMENT

TASK 3 SPACE STATION SERVICING FACILITY CONCEPTS

SATELLITE/MISSION CLASSES AND SERVICING FUNCTIONS

The chart shows principal servicing functions to be performed in representative satellite or mission classes. The first three lines list servicing functions on the Space Station (SS) itself, its subsystems or attached payloads. Some of the functions such as inspection, test, checkout, module replacement and resupply of consumables are required in many of the missions. Control of rendezvous and docking or berthing is involved whenever a satellite is being retrieved for servicing or when it is to be serviced remotely by an Orbiting Maneuvering Vehicle (OMV) or Orbital Transfer Vehicle (OTV) equipped with a servicer attachment.

Most of the functions shown lend themselves to automated operations, i.e., teleoperated or robotic servicing as an alternative to direct crew involvement. In the case of in-situ servicing, the alternatives are teleoperation by radio command and video feedback or fully robotic operation.

SATELLITE/MISSION CLASSES AND SERVICING FUNCTIONS

SATELLITE OR MISSION CLASS	SERVICING FUNCTION	SATELLITE ASSEMBLY ON SS										SATELLITE LAUNCH FROM SS										SERVICE SPACE PLATFORM									
		DEPLOYMENT	CONTROL RENDEZVOUS & DOCKING	INSPECTION	RETRIEVAL	ORBITAL ASSEMBLY	MaintenANCE	TEST/CHECKOUT	REPAIR/MODIFICATION	CHANGING, RE-	REPLACEMENT	EARTH RETURN	RESUPPLY	EMERGENCY OPS.																	
SPACE STATION BUILDUP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
SS MODULE REPLACEMENT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
SERVICE SS ATTACHED P/L	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
SERVICE RETRIEVED	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
SERVICE LEO SATELLITE, IN-SITU	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
SERVICE GEO SATELLITE IN-SITU	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
SATELLITE ASSEMBLY ON SS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
SATELLITE LAUNCH FROM SS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
SERVICE SPACE PLATFORM	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					

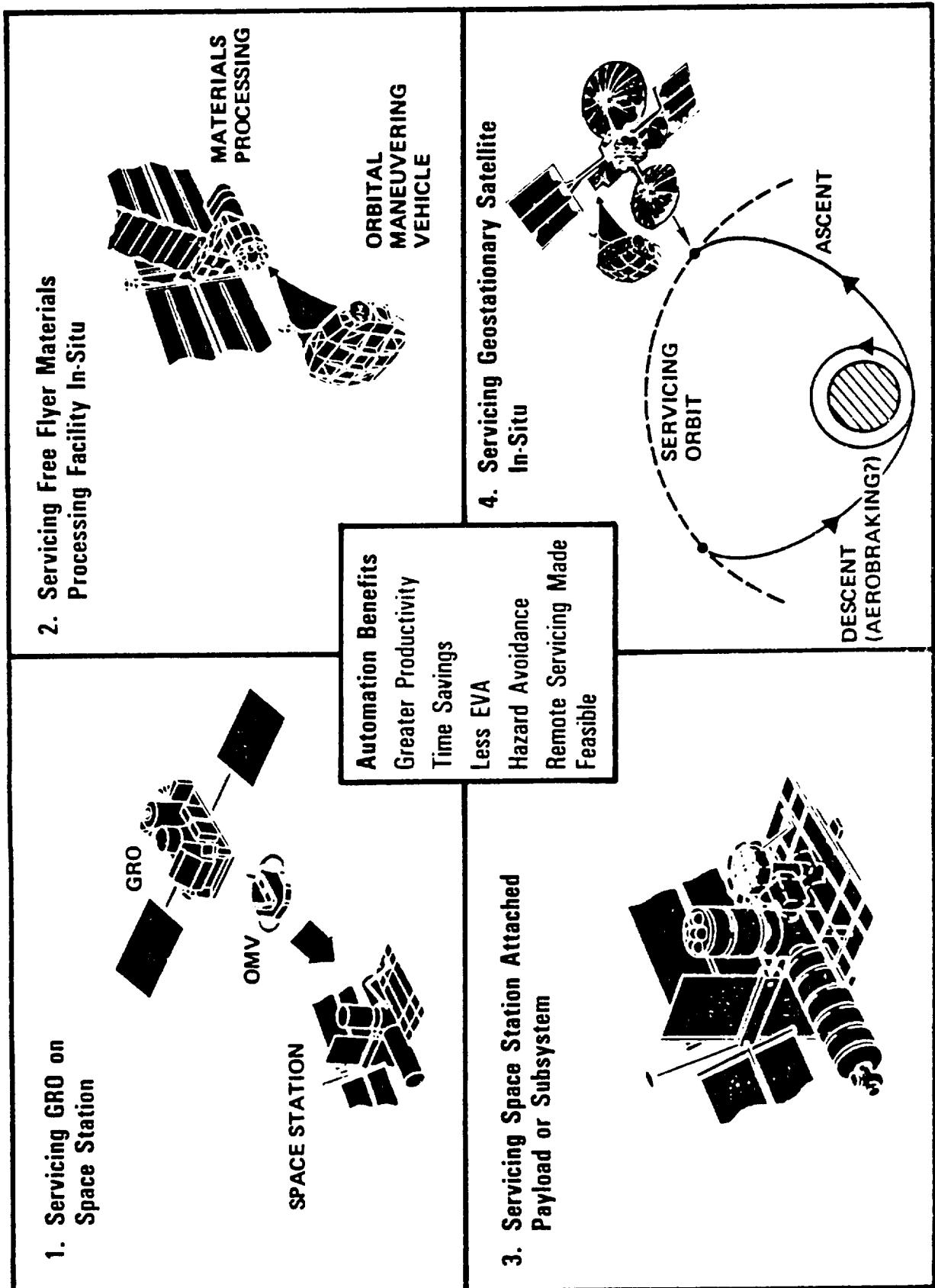
AUTOMATED SERVICING REFERENCE MISSIONS

TRW's study approach involved, as a first step, a review of the NASA mission model of the 1980s and 1990s and an assessment of likely servicing requirements. However, rather than covering the many projected missions, we concentrated on four representative mission scenarios which encompassed the most relevant aspects of servicing functions to be performed either on board the Space Station itself or remotely at the orbital position of the target satellites. The reference mission scenarios were:

1. Servicing of a low-earth-orbit (LEO) satellite, e.g., the Gamma Ray Observatory (GRO), at the Space Station with orbit transfer by an Orbital Maneuvering Vehicle.
2. Servicing of a free-flying, co-orbiting materials processing facility, *in situ*, including periodic resupply and harvesting of finished products.
3. Repair/refurbishment or changeout of Space-Station-attached payloads or subsystems.
4. Servicing of a geostationary satellite, *in situ*, by using a recoverable Orbital Transfer Vehicle to perform the ascent and descent to/from synchronous orbit, carrying supplies, replacement parts, tools and support equipment such as a remote/robotic servicer.

These reference missions are derived from a set of servicing technology development missions (TDMs) previously studied by TRW under NASA/MSFC contract NAS 8-35081 to which this automation study task was subsequently added.

The insert in the center of the chart summarizes principal benefits accruing from automated servicing.



Levels and modes of automation to be utilized for servicing will depend on the nature of the tasks, the location where the service is being performed (on the Space Station or in-situ), and on the state of technology evolution at the time of the mission.

The chart summarizes the use of teleoperation (T), robotics (R) and artificial intelligence/knowledge-based system support (A) in the four missions investigated, and the use of multiple-purpose data system support (D) other than for artificial intelligence. Mixed entries (T/R, D/A) indicate that both modes will be utilized depending on the specifics of the task, or in some instances, a preference for the more advanced technology (robotics, artificial intelligence) if it is available at the time of the mission. Consider, for example, the entries for mating/demating in the fifth row under teleoperation or robotics. In Mission 1 (GRO refueling) the mating and demating functions are performed at the Space Station and utilize teleoperation. In Mission 2 (Materials Processing Service in-situ) some of the functions are performed onboard the Space Station (T) and some in-situ (T or R). In Mission 4 (geostationary servicing) the in-situ functions are primarily performed in the robotic mode.

On the whole, it is apparent that teleoperation requirements are more numerous than robotics requirements, at least in the early Space Station operations phase. Also during this phase there will be a need for data system support across the entire mission spectrum and for most of the functions indicated, while artificial intelligence support requirements increase with Space Station evolution.

The results also indicate much commonality in the application and use of automated servicing equipment and capabilities, once they become available. This has favorable implications as to the projected cost-economy of automated servicing technology developments.

AUTOMATION REQUIREMENTS IN SELECTED REFERENCE MISSIONS

TYPE OF AUTOMATION	SERVICING REFERENCE MISSION			
	1. GRO REFUELING ON SS	2. MAT. SERVICE IN SITU	3. P/L OR S/S CHANGEOUT ON SS	4. GEO-SAT. SERVICE IN SITU
<u>TELEOPERATION (T) OR ROBOTIC CONTROL (R)</u>	(1)	T/R	T	T/R
• EQUIPMENT LOADING/UNLOADING, HANDLING	T	T	T	T
• SATELLITE BERTHING, RELEASING	T	T	T	T
• LOAD TRANSFER BY RMS OR RAIL SYSTEM	T	T/R	T	R
• MODULE CHANGEOUT (LOCAL, REMOTE)	T	T/R	T	T/R
• MATING/DEMATING UNITS OR UMBILICALS	T	T	-	T/R
• PROPELLANT, FLUID TRANSFER	T	T	-	T/R
• OMV, OTV MANEUVER CONTROL	T/R	T/R	T	T/R
• VISUAL INSPECTION	T	T/R	T	T/R
<u>DATA SYSTEM SUPPORT (D) OR ART INTELL. (A)</u>	(2)	D/A	D/A	D/A
• MISSION AND TASK PLANNING, SEQUENCING	D	D	-	D
• ORBIT TRANSFER, MANEUVER OPTIMIZATION	D	D	D	D
• DATA PROCESSING, RETRIEVAL, DISPLAY	D	D/A	D	D/A
• AUTOMATED TESTS AND CHECKOUT	D	A	A	A
• DIAGNOSTICS, TROUBLE SHOOTING ASSISTANCE	A	D/A	D/A	D/A
• LOGISTICS PLANNING	D/A	D/A	-	D/A
• COMMUNICATION, TRAFFIC CONTROL	D/A	D/A	-	D/A

(1) T/R - TELEOPERATION (EARLY MISSIONS) OR ROBOTICS (LATER MISSIONS) OR BOTH MODES
(2) D/A - DATA SYST. SUPPORT AND/OR ART. INTELLIGENCE SUPPORT (LATER MISSIONS)

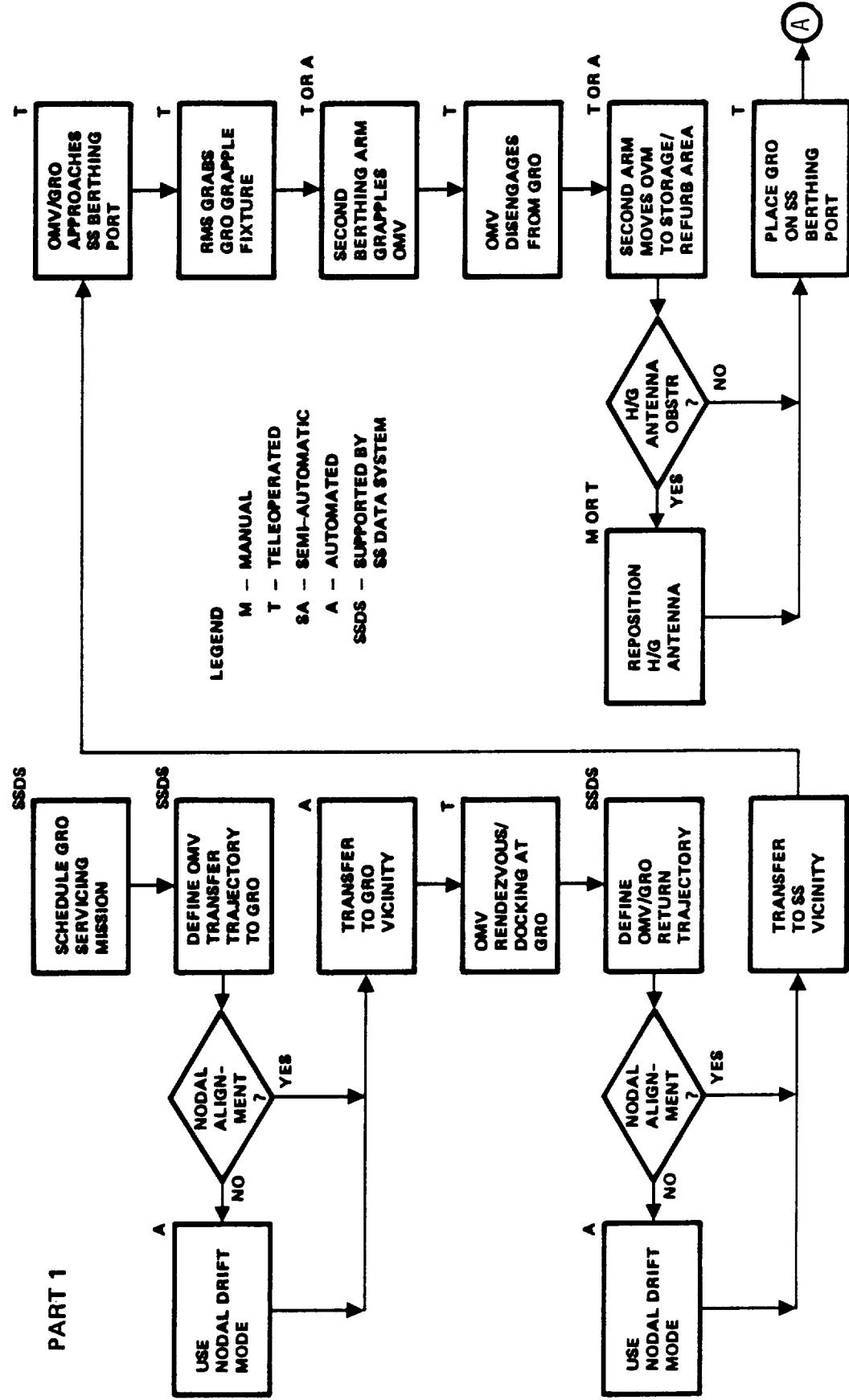
EVENT FLOW - REFERENCE MISSION NO. 1
GRO REFUELING

Detailed event sequences and automation requirements were determined for each of the four selected reference missions. The facing chart shows the event flow for Reference Mission No. 1 (GRO refueling) with an indication of those activities where manual (M), automated (A), semi-automated (SA), or teleoperation (T) functions are assumed. The designation SSDS refers to support by the SS integrated data system. The sequence continues as shown on the next chart.

It is apparent that a large majority of steps in this sequence call for teleoperated, semi-automated or fully automated (robotic) action. Manual operation, requiring EVA by the crew, is involved in connecting and disconnecting umbilical lines and repositioning the high gain antenna boom if it protrudes in a direction that interferes with placing the satellite on the SS servicing platform or berthing fixture. However even these manual operations may eventually be automated to reduce EVA sorties and save time.

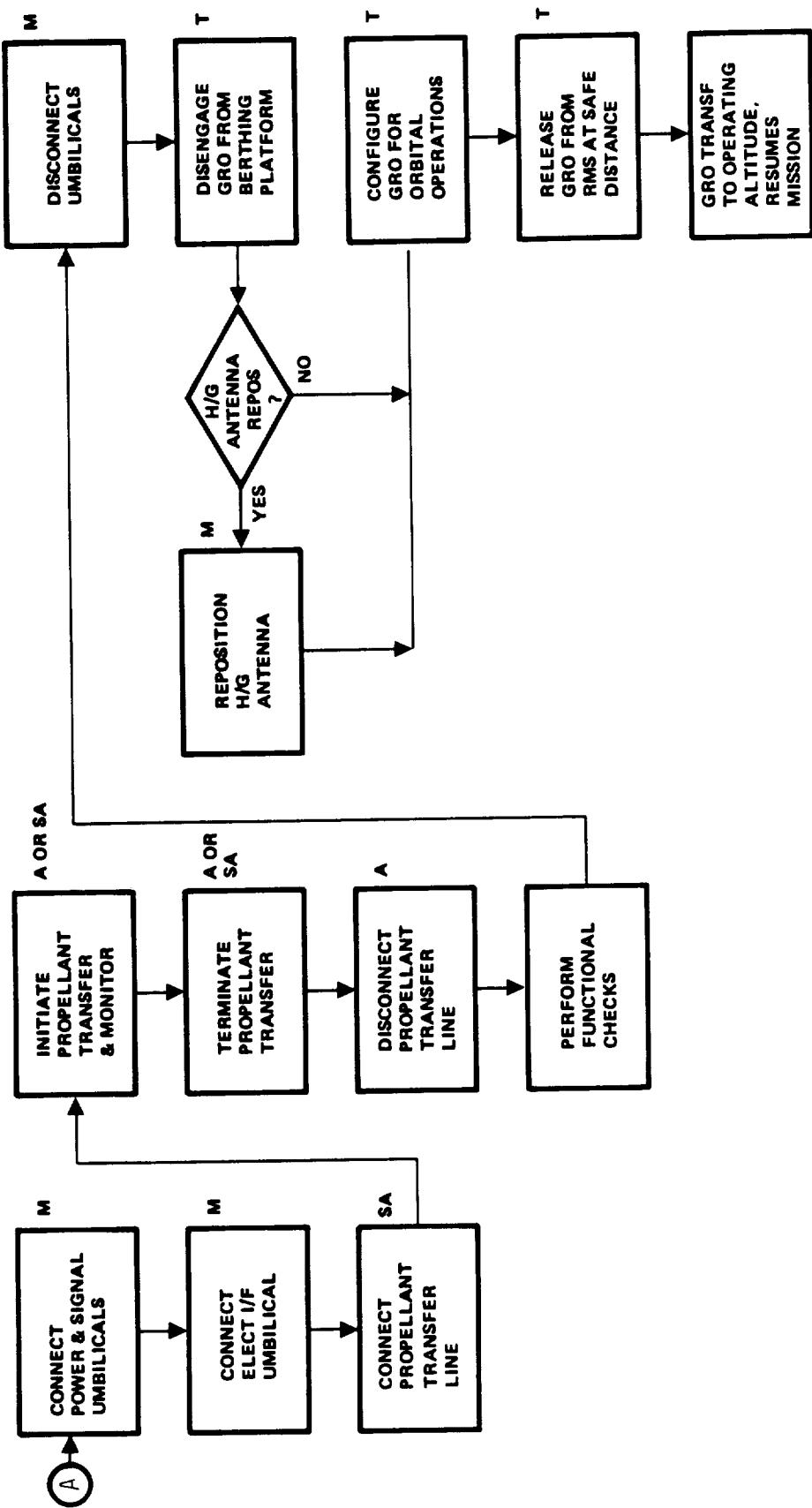
Actual early GRO refueling missions to be performed on board the Shuttle orbiter call for direct EVA crew involvement in many instances where this chart projects automated functions in future SS servicing of GRO-type satellites.

EVENT FLOW - REFERENCE MISSION NO. 1
GRO REFUELING



EVENT FLOW - REFERENCE MISSION NO. 1
GRO REFUELING (CONTINUED)

PART 2



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TOP LEVEL SCENARIO - REFERENCE MISSION 1
GRO REFUELING

To further illustrate event sequences the facing chart and its continuation on the next two charts present additional details of the Reference Mission 1 scenario, identify the crew involvement (EVA or IVA), list automation requirements, and give time estimates for performing each task, with and without the use of automated system support. The time estimates cover only those activities that involve crew functions and, thus reflect potential time savings resulting from automated system use. Not accounted for are time intervals that are not relevant to the comparison, such as the time elapsed during orbit transfer to and from the Space Station. It was found that in the activities accounted for, 50 percent of crew time can be saved by using automated servicing support, often eliminating time-consuming preparation for and completion of EVA tasks.

Corresponding scenario details were determined for the three other reference missions. Automated servicing support was found to save from 40 to 60 percent of crew time in these missions.

TOP LEVEL SCENARIO - REFERENCE MISSION 1
GRO REFUELING

ACTIVITY/FUNCTION	CREW TASK	AUTOMATION REQUIREMENT	EST. TIME (MINUTES) WITH/WITHOUT AUTOMATION
1 Schedule GRO servicing		DS support	
2 Determine required support equipment and supplies	EVA	DS support	30
3 Receive needed equipment and supplies from ground via STS		Automated unloading and stowage	60
4 Determine optimal GRO retrieval mission profile by DMV	EVA	DS support	60
5 Prepare OMV for retrieval mission (incl. propellant addition if required)	EVA	Automated handling of new propellant tanks if required	120
6 Launch OMV from SS and perform orbital transfer to GRO vicinity	IVA	DS support and automated command sequence	60
7 Deactivate GRO	IVA	Remotely controlled by crew/automated sequence	20
8 Perform OMV rendezvous and docking to GRO		Automated command sequence	60
9 Orbital transfer of GRO to SS by OMV			

TOP LEVEL SCENARIO - REFERENCE MISSION 1
GRO REFUELING (CONT'D)

ACTIVITY/FUNCTION	CREW TASK	AUTOMATION REQUIREMENT	EST. TIME (MINUTES) WITH/WITHOUT AUTOMATION
10 Perform rendezvous and docking of GRO/OMV at SS with aid of SS manipulator arm (RMS)	IVA	Remotely controlled or supervised by crew (automated sequence)	20 60
11 Secure GRO to SS berthing port and connect umbilical(s)	IVA/ EVA	RMS, teleoperation	20 140
12 Detach and stow OMV	EVA	Teleoperation	15 60
13 Inspect GRO and perform comprehensive checkout	EVA	DS support	20 60
14 Determine source of malfunctions if any	IVA	Expert system support from DS	15 45
15 Transfer replacement units (ORU) from storage area	EVA	Teleoperation, automated handling and transfer	15 45
16 Replace failed units on GRO	EVA	Automated handling	15 45
17 Check out GRO for proper functioning with new units	IVA/ EVA	DS support	15 15
18 Connect propellant transfer line	EVA		300 300
19 Perform propellant transfer to GRO	IVA	Automated sequence	

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TOP LEVEL SCENARIO - REFERENCE MISSION 1
GRO REFUELING (CONT'D)

ACTIVITY/FUNCTION	CREW TASK	AUTOMATION REQUIREMENT	EST. TIME (MINUTES) WITH/WITHOUT AUTOMATION
20 Disconnect and stow propellant line	EVA		15 15
21 Checkout and prepare GRO for departure in operational configuration	IVA/ EVA	DS support, automated sequence	60 120
22 Disconnect umbilical(s)	IVA/ EVA	Teleoperation	15 115
23 Deploy GRO by RMS and release	IVA	Teleoperation, automated sequence	15 15
24 GRO transfers to operational altitude and resumes operation		Remotely controlled, automated sequence	
25 Verify normal operation of GRO		Monitoring sequence, supported by DS	
			Total of activities accounted for
			535 1230 (10.5 hr.) (20.5 hr.)

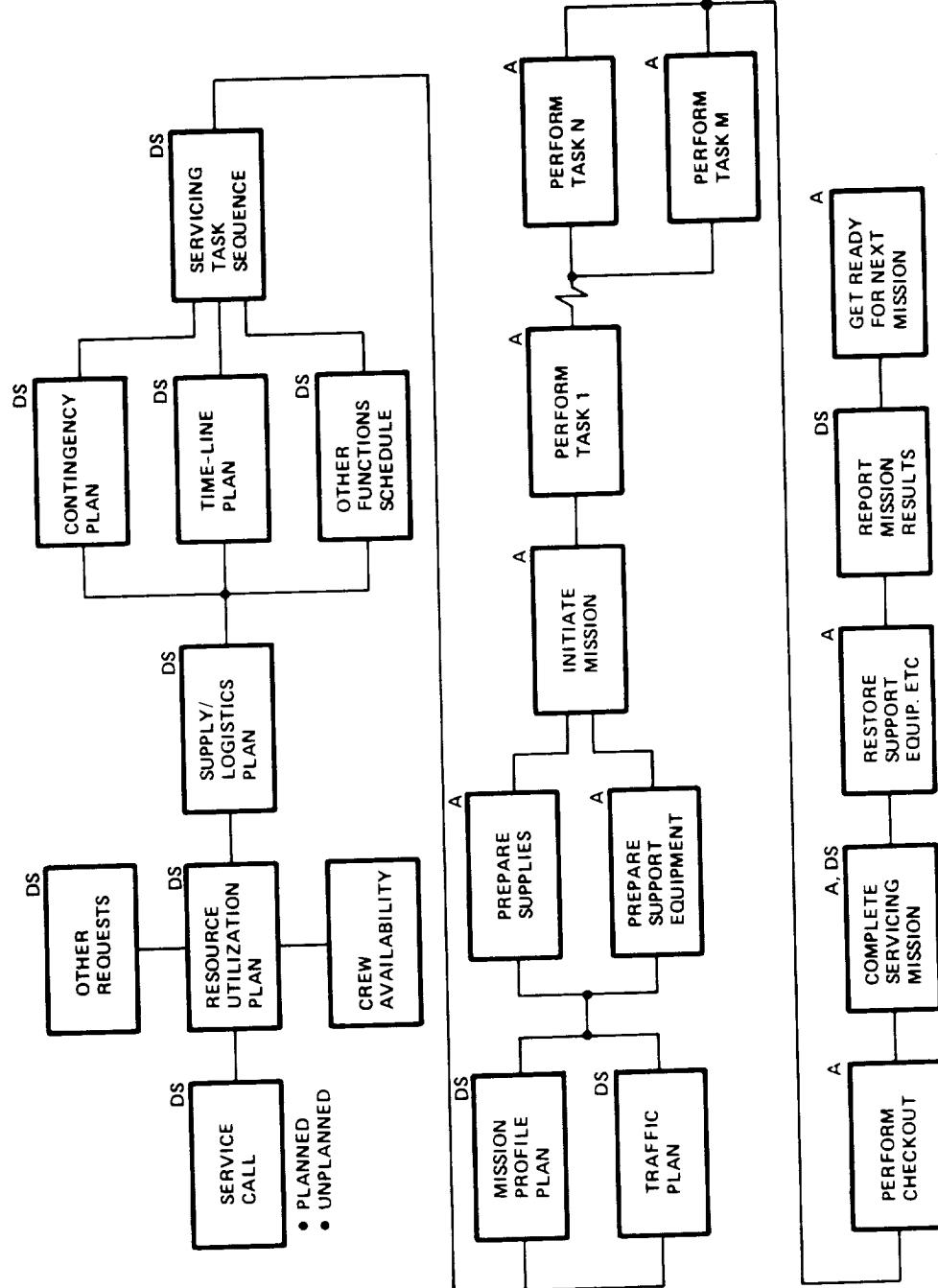
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SERVICING MISSION PLANNING AND EXECUTION

The chart illustrates the important role of Space Station data system support in the planning and execution of a typical servicing mission. The sequence of activities required to perform the mission, starting from the time a call for service is received, is indicated by the flow of major operational steps including resource utilization planning, logistics planning, mission profile planning, preparation of supplies and support equipment through task execution and final checkout.

A large share of these events depends heavily on data system support (indicated by DS). Physical activities involved in carrying out the mission, although not specifically accounted for, are assumed to involve automated equipment support (indicated by A) and often also support by the data system.

Servicing Mission Planning and Execution



A – AUTOMATED SYSTEM SUPPORT

DS – DATA SYSTEM SUPPORT

2. STUDY RESULTS

TASK 1 AUTOMATED SERVICING REQUIREMENTS

TASK 2 AUTOMATED SERVICING TECHNOLOGY ASSESSMENT

TASK 3 SPACE STATION SERVICING FACILITY CONCEPTS

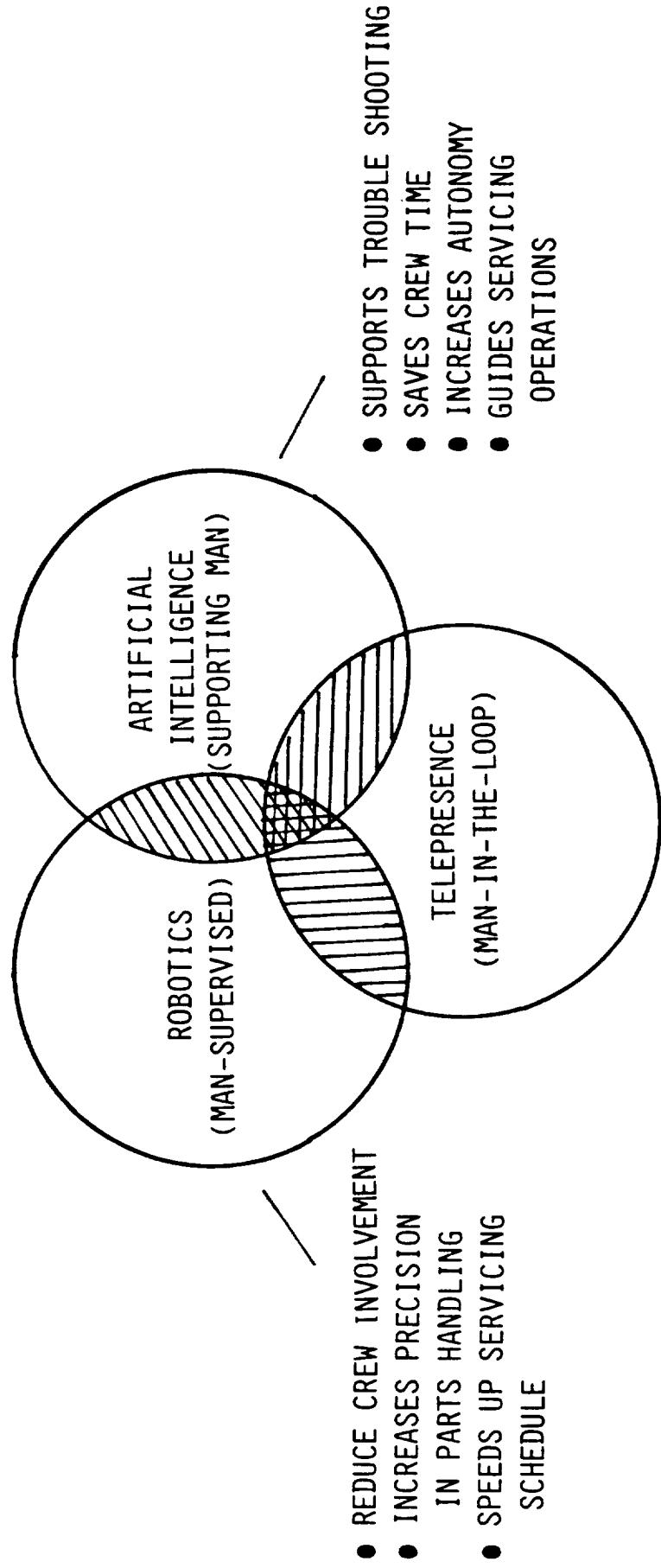
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AUTOMATION DISCIPLINES APPLIED TO SATELLITE SERVICING

The chart shows a logic diagram which defines interrelations between the three principal automation technologies or disciplines used in supporting satellite servicing, and their role in relation to man's functions and tasks. The shaded overlapping areas represent applications that involve joint utilization of more than one of the three technologies, as for example in situations where a remote manipulator is controlled either by teleoperation, with the "man in the loop", or autonomously as robot (usually man-supervised). Teleoperation may be a backup option where robotic use of the manipulator is unable to handle unforeseen aspects of a specific task.

Our use of the terminology and distinctions between automation disciplines conforms with the definitions listed in front of this volume.

Although not shown in the chart, the Space Station data system plays a major role in providing a critically important link or infrastructure to most or all automated activities.



KEY AUTOMATION TECHNOLOGIES USED FOR SATELLITE SERVICING

The chart lists 12 key automation technologies used in support of servicing activities and defines the types of benefit, such as speeding up task performance, reduction of crew task loading, enhancement of crew safety, and enabling of remote servicing missions. The last column indicates that most or all of the four reference missions benefit from these automated functions, i.e., there exists a high degree of commonality in automated equipment requirements.

The order in which these technologies are listed reflects a ranking of priorities or time-phased requirements in their expected utilization in satellite servicing tasks.

Two subsequent charts will show an assessment of the state-of-technology of these items and a projected schedule of evolution from initial demonstration to the early and advanced states of development.

**KEY AUTOMATION TECHNOLOGIES USED
FOR SATELLITE SERVICING**



TECHNOLOGY/AUTOMATED FUNCTION	PRINCIPAL BENEFITS	APPLIES TO REF. MISSIONS
1. DEXTEROUS MANIPULATOR, INCLUDING SPECIAL PURPOSE END EFFECTORS	<ul style="list-style-type: none"> • HANDLES DELICATE TASKS • USED IN T/O OR ROBOTIC MODE (SEE ITEM 3) 	ALL
2. SERVICING-COMPATIBLE SPACECRAFT	<ul style="list-style-type: none"> • ENABLES AUTOMATED SERVICING 	ALL
3. SPACE-QUALIFIED ROBOT, ROBOTIC SERVICING	<ul style="list-style-type: none"> • SAVES CREW TIME • ENHANCES CREW SAFETY • ENABLES REMOTE SERVICING 	ALL
4. DATA SYSTEM SERVICING SUPPORT	<ul style="list-style-type: none"> • ENHANCES CREW PRODUCTIVITY • SAVES TIME 	ALL
5. ADVANCED MAN-MACHINE INTERFACES (INCLUDING VOICE RECOGNITION, VOICE RESPONSE, HEADS-UP DISPLAY TECHNOLOGY)	<ul style="list-style-type: none"> • ENHANCES CREW PRODUCTIVITY • SAVES TIME • REDUCES CREW ERRORS 	ALL
6. ADVANCED FLUID TRANSFER SYSTEM	<ul style="list-style-type: none"> • SAVES TIME • ENHANCES CREW SAFETY • ENABLES OTV SUPPORTED MISSIONS 	1,2,4

KEY AUTOMATION TECHNOLOGIES USED FOR
SATELLITE SERVICING (CONTINUED)

7. ROBOT VISION SYSTEM APPLIED TO	<ul style="list-style-type: none"> • ENABLES AUTONOMOUS REMOTE SERVICING • ENABLES ROBOTIC ASSEMBLY, MODULE EXCHANGE 	ALL
8. AUTOMATED LOAD HANDLING AND TRANSFER	<ul style="list-style-type: none"> • SAVES CREW INVOLVEMENT • SPEEDS UP SERVICING 	ALL
9. AUTOMATED RENDEZVOUS/DOCKING (PRECISION RANGE, RANGE RATE AND ATTITUDE DETERMINATION)	<ul style="list-style-type: none"> • ENHANCES REMOTE SERVICING • SAVES TIME, REDUCES CREW TASK LOAD 	1,2,4
10. SMART FRONT END ON OMV, OTV	<ul style="list-style-type: none"> • ENABLES AUTONOMOUS REMOTE SERVICING 	1,2,4
11. KNOWLEDGE-BASED SYSTEMS SUPPORTED SERVICING	<ul style="list-style-type: none"> • ENHANCES DIAGNOSTIC CAPABILITY • STREAMLINES SERVICING • OPERATIONS • ENHANCES SS SERVICING AUTONOMY 	ALL
12. REUSABLE OTV	<ul style="list-style-type: none"> • ENABLES REMOTE SERVICING AT MEO AND GEO ALTITUDES 	47

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ROBOT TECHNOLOGY ADAPTATION TO SPACE STATION USE

The chart addresses the question of which features of currently available terrestrial robotics may be directly applicable to use on the Space Station (left hand column).

The highly developed industrial robot technology provides many features also needed on the Space Station and in satellite servicing such as electro-mechanical design and articulation, computer control, versatility, and programming/teaching principles.

The right hand column lists those issues where major adaptations or modifications are required for robots to work in the new and hostile space environment.

Environmental concerns are primarily those of materials selection, thermal protection, and lubrication techniques. Terrestrial robots generally are designed to work within and exploit the gravity effects that exist on the ground. The design will require modification to operate in zero gravity.

The key issue will be flexibility and adaptability to a great variety of operating conditions and tasks to meet the diversity of satellite servicing functions. Robot applications in space-based manufacturing or structural assembly typically are repetitive in character and therefore would require less flexible designs.



APPLICABLE KEY FEATURES

- ELECTRO-MECHANICAL DESIGN AND ARTICULATION
- COMPUTER CONTROL CHANNELS
- SENSING TECHNIQUES
- DYNAMIC RESPONSE
- DEXTERITY
- PRECISION
- EXCHANGEABLE END EFFECTORS
- PROGRAMMING/TEACHING ROUTINES

ADAPTATION REQUIREMENTS

- WEIGHT REDUCTION
- COMPACT LAUNCH CONFIGURATION
- PROTECTION AGAINST SPACE ENVIRONMENT:
 - MATERIALS
 - THERMAL
 - LUBRICATION
- ZERO-g COMPATIBILITY
- ADDED SAFEGUARDS
- OPERATION FLEXIBILITY
- MOBILITY

AUTOMATED SERVICING TECHNOLOGY ASSESSMENT

The chart is a first cut at assessing the current state of development of the twelve items previously listed as key technologies for the support of satellite servicing. Those required in the earliest servicing missions on the IOC Space Station are expected to be available in the near-term. Many of the technologies for more advanced missions fall in the intermediate category. Longer-term development is needed for items 8, 11, and 12. Knowledge-based systems (or expert systems) will be required to support autonomous, fully robotic servicing functions including automated diagnostics and trouble shooting, and response to contingencies. The reusable orbital transfer vehicle (OTV) will require technology advances to enable in-situ servicing missions to geostationary satellites, not expected to occur before the late 1990s.

The table identifies the listed items as "enabling" or "enhancing" technologies, and ranks priorities on a scale of 1 to 3. Seven of the 12 key technologies have top priority ranking.

AUTOMATED SERVICING TECHNOLOGY ASSESSMENT



KEY TECHNOLOGY	STATE OF TECHNOLOGY			PRIORITY RANKING
	NEAR TERM	INTERMEDIATE	LONGER TERM	ENHANCING TECHNOLOGY
1. DEXTEROUS MANIPULATORS, INC. SPECIAL END EFFECTORS	X	X	X	1
2. SERVICING/AUTOM. SERVICING COMPATIBLE SATELLITES AND PAYLOAD UNITS	X	X	X	1
3. SPACE-QUALIFIED ROBOTS, ROBOTIC SERVICING	X	X	X	1
4. DATA SYSTEM SERVICING SUPPORT	X	X	X	1
5. ADVANCED MAN-MACHINE INTERFACES	X	X	X	1
6. ADVANCED FLUID TRANSFER SYSTEMS	X	X	X	1
7. ROBOT-VISION CONTROLLED SERVICING	X	X	X	1
8. AUTOMATED LOAD HANDLING/TRANSFER	X	X	X	2
9. AUTOMATED RENDEZVOUS/BERTHING AND PROXIMITY OPERATIONS	X	X	X	2
10. OMV WITH SMART FRONT END	X	X	X	2
11. KNOWLEDGE-BASED SYSTEM SUPPORT (TROUBLE SHOOTING, PLANNING, CONTINGENCY RESPONSE)	X	X	X	3
12. REUSABLE OTV	X	X	X	3



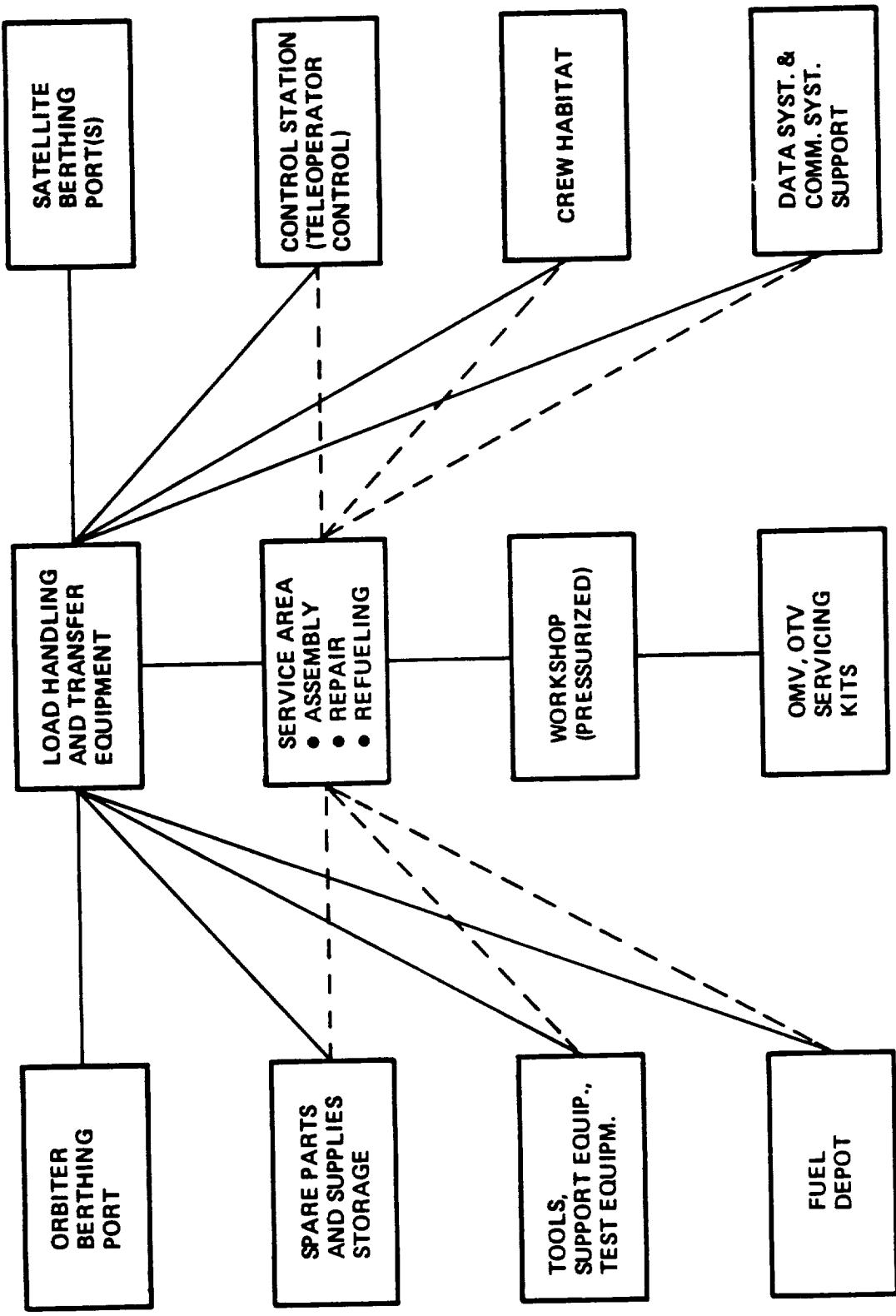
- 2. STUDY RESULTS
- TASK 1 AUTOMATED SERVICING REQUIREMENTS
- TASK 2 AUTOMATED SERVICING TECHNOLOGY ASSESSMENT
- TASK 3 SPACE STATION SERVICING FACILITY CONCEPTS

ELEMENTS OF SATELLITE SERVICING FACILITY

The satellite servicing facility on the Space Station should be viewed as a collection of many elements scattered in different locations. The chart shows these elements and their interactions as indicated by solid or dashed lines. The chart shows these reflect interactions that occur continuously or most often. Among those elements shown in the chart, those in the upper and right hand parts dominate in defining the degree or level of traffic and activity, i.e., orbiter and satellite berthing ports, load handling and transfer equipment, the control station, data management and communications systems, and the service areas assigned to assembly, repair, and refueling.

Illustrations shown in subsequent charts will provide examples of the layout, the support equipment, and other features of a generic servicing facility concept.

ELEMENTS OF SATELLITE SERVICING FACILITY



LEGEND

INTERACTIONS OCCURRING MOST OFTEN

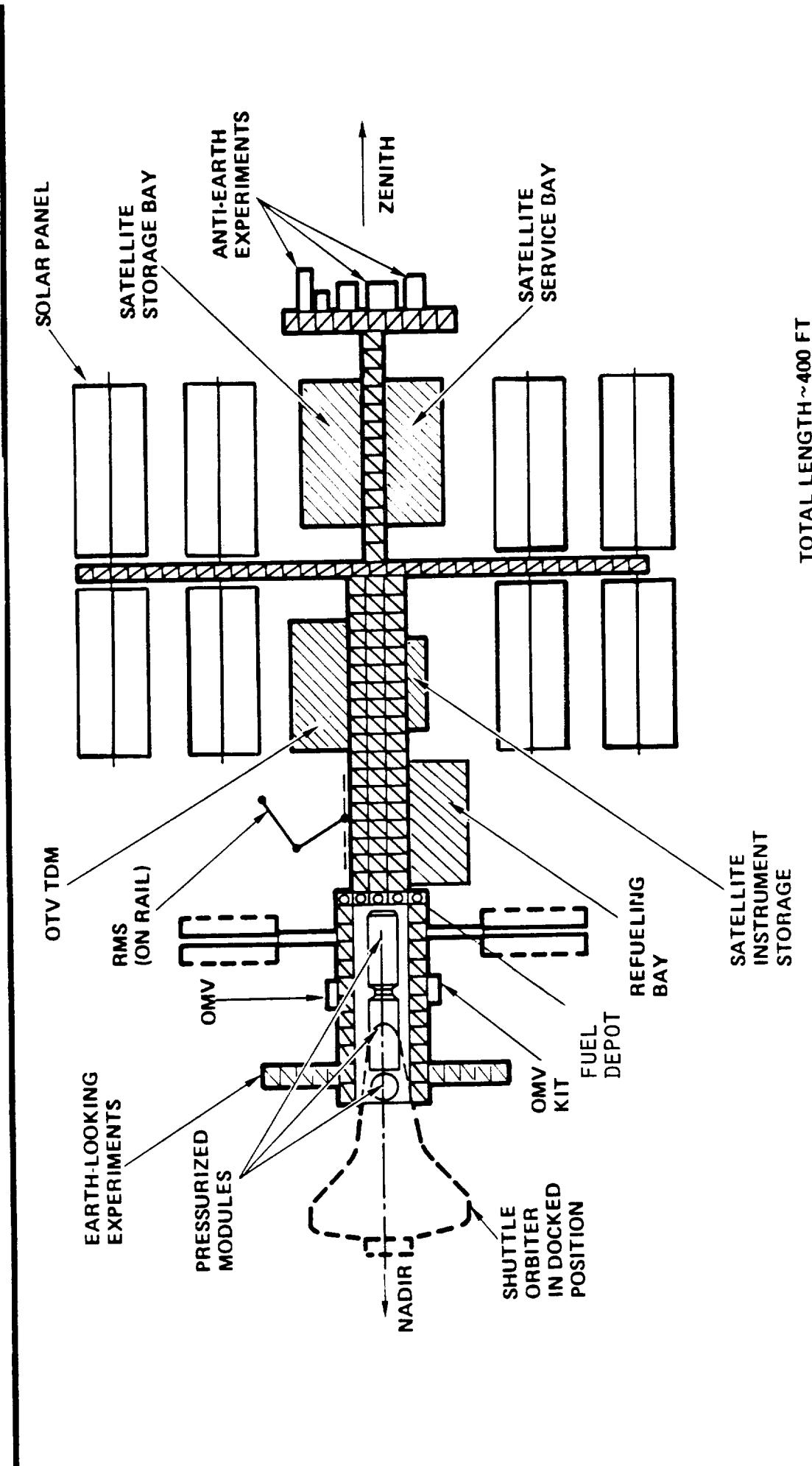
LESS OFTEN

SPACE STATION DESIGN FEATURES RELATED TO SATELLITE SERVICING
(REFERENCE IOC CONFIGURATION)

We used NASA's current Space Station IOC reference configuration, also known as the "power tower", as baseline in selecting a generic satellite servicing concept. The chart shows a simplified drawing of this configuration and indicates areas and features involved with servicing activities. They include satellite storage and service bays, instrument storage, a refueling bay located next to the fuel depot, a bay for accommodating the future OTV and for handling OTV technology development, and storage for the OMV and OMV servicer kits.

A major issue involves servicing on a centralized or decentralized facility. A centralized facility would provide some convenience in terms of close proximity of all servicing related locations and storage areas and would reduce load transfer requirements. A decentralized facility on the other hand reduces local congestion and facilitates growth. It generally emphasizes automated and teleoperated approaches to servicing.

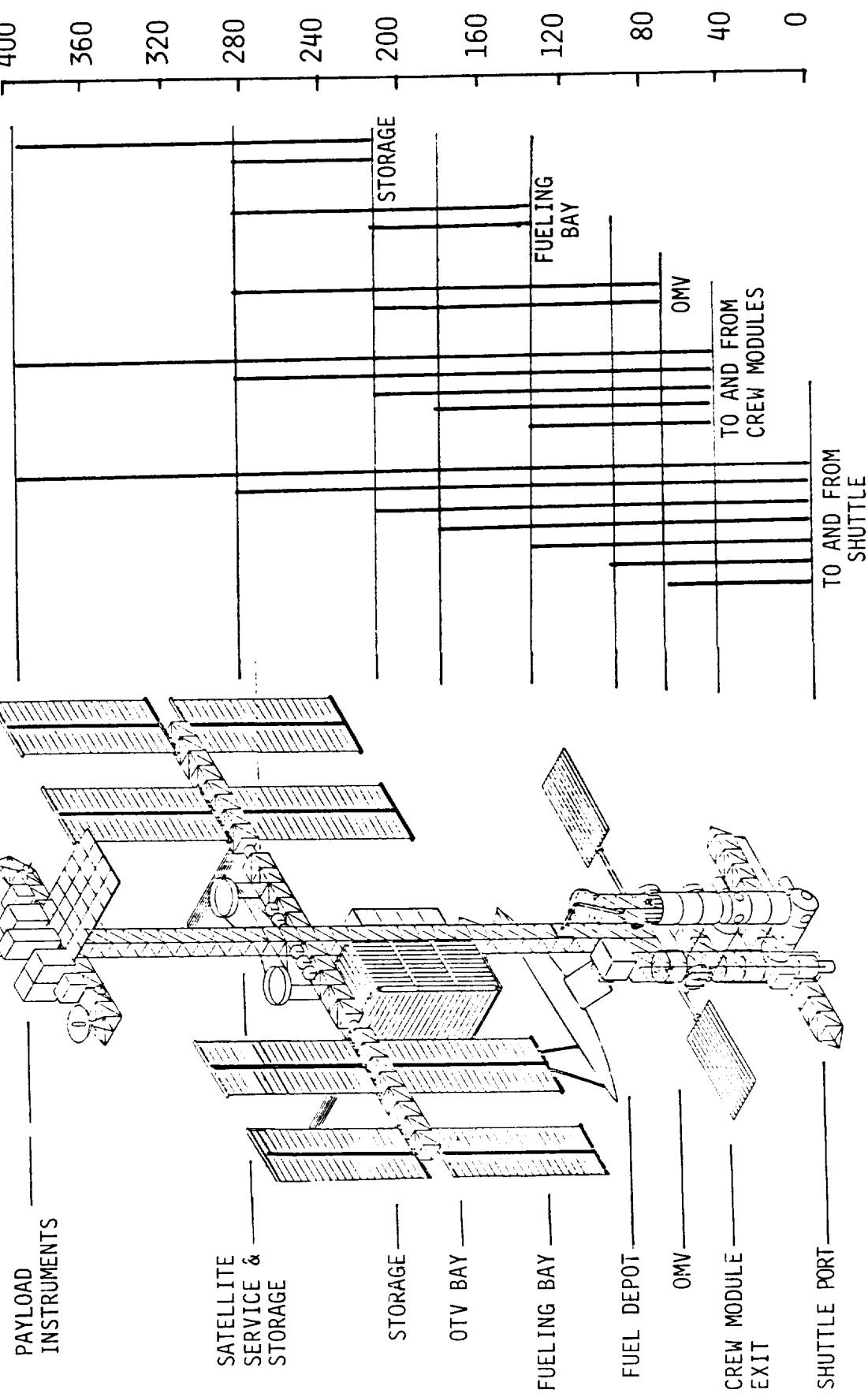
SPACE STATION DESIGN FEATURES
RELATED TO SATELLITE SERVICING
(REFERENCE 10C CONFIGURATION)



SERVICING TRAFFIC FLOW ISSUES

The dispersed location of service related facilities on the reference configuration with maximum separation of 400 ft. along the keel implies a need for convenient load transfer and support of servicing traffic. The chart serves to illustrate traffic patterns ranging from one end of the keel to the other and for short distances between areas of principal servicing activity. This includes crew movements from/to the habitat, the work and storage areas, and load transfer requirements between the Shuttle berthing port, storage facilities, work stations, the fuel depot and the satellite berthing port. Fast and convenient load transfer, locally or remotely controlled, and effective traffic flow planning supported by the Space Station data system are major design considerations.

SERVICING TRAFFIC ALONG SPACE STATION KEEL



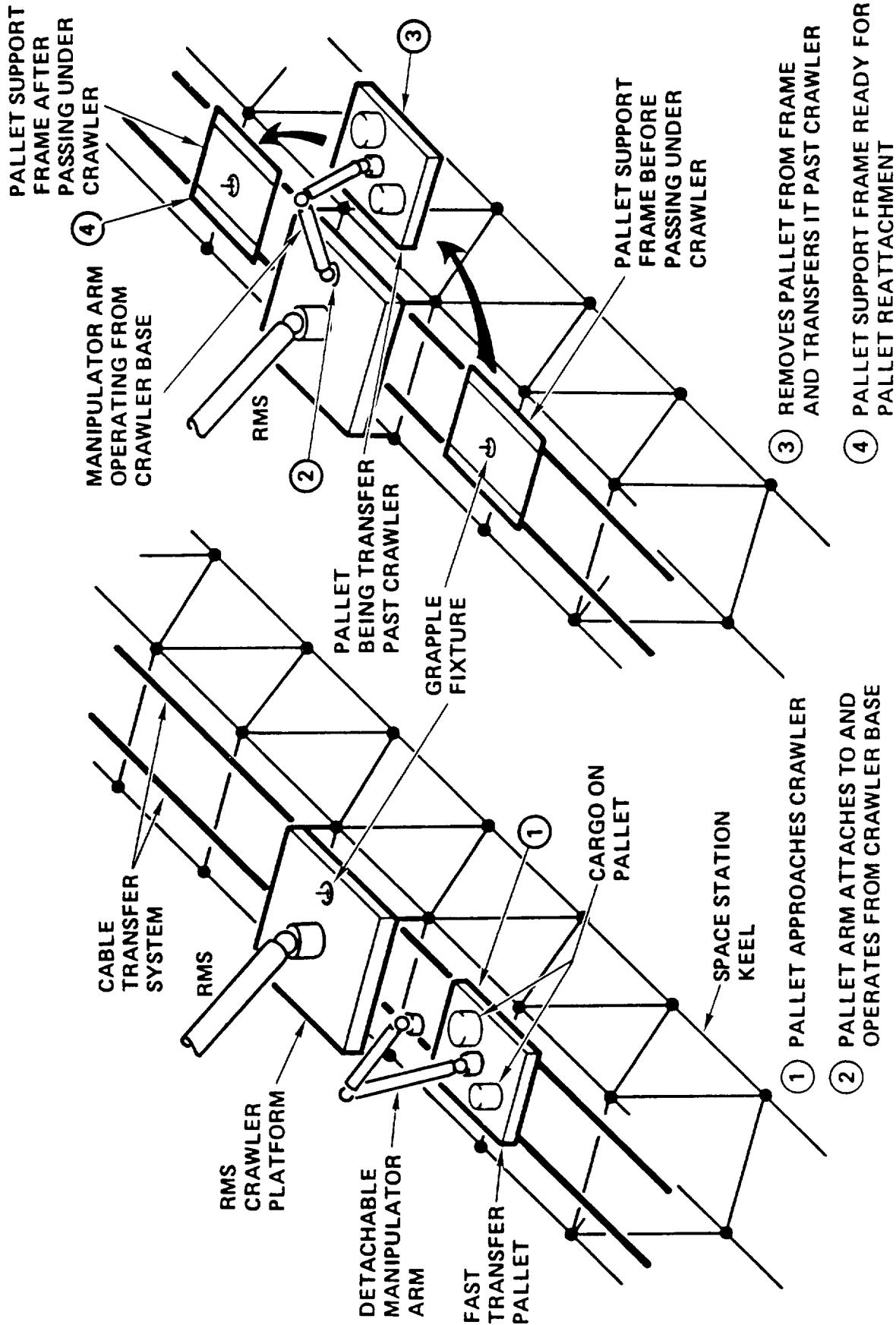
CABLE-DRIVEN PALLET TRANSFER CONCEPT

The dispersed location of service areas avoids crowding and permits unconstrained access but also necessitates more extensive and frequent transfer of crew men, support equipment, satellite hardware, tools and supplies along the Space Station keel. Traffic volume is expected to increase as demand for servicing expands with Space Station growth.

A fast and efficient system for load handling and transfer will be required to support servicing operations. The Shuttle manipulator arm (RMS) with its nearly 50 ft reach can handle load transfers locally from a fixed position, or by moving on its platform along the Space Station keel structure. The crawling platform concept developed by NASA/JSC allows the system to move step by step, from one structural node to the next, thus being able to move along the entire keel as well as the solar array panel support booms, albeit at very low speed.

An auxiliary smaller and faster-moving transportation system using rails or cables would increase load handling and transfer flexibility and speed. The chart shows a cable-driven pallet concept which can transfer loads many times faster than the RMS crawler platform. The pallet can pass underneath the crawler platform or can be manipulated around it so that mutual obstruction is avoided. A detachable manipulator with 10 to 15 ft reach can be used locally for load handling before and after transfer. With its free end the manipulator can plug into power/control terminals along the cable way being designed to be operated from either one of its end joints by a reciprocal articulation technique.

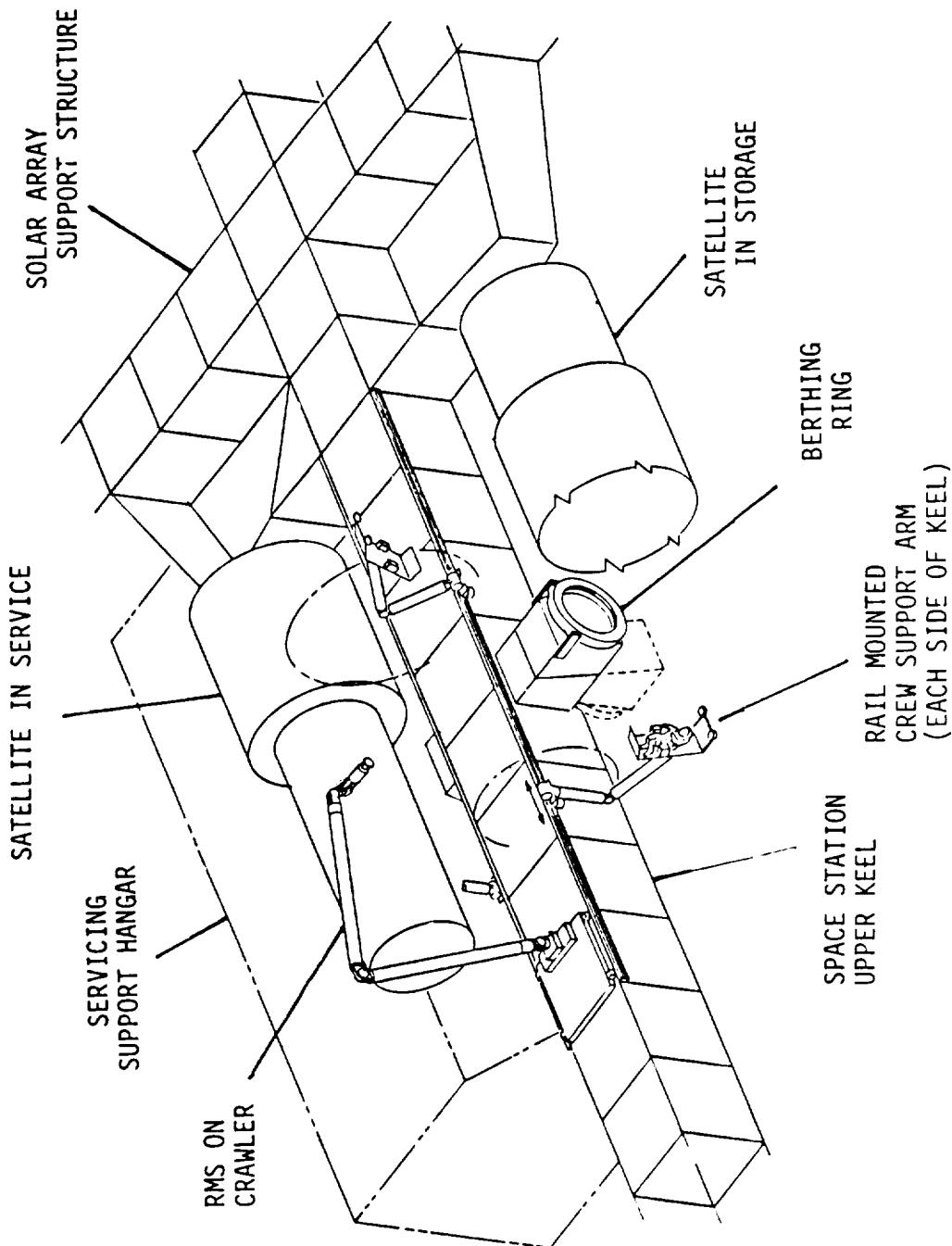
CABLE-DRIVEN PALLET TRANSFER CONCEPT



ACCESS TO SATELLITES BEING STORED AND SERVICED

As shown in the chart, the satellite berthing port and the service bay are placed in close proximity, thereby facilitating satellite transfer between the two. Incoming satellites may be retained in the berthing location if the service bay is occupied. Satellite exchange between the two locations will be expedited by use of two manipulator arms.

Rail-mounted crew support areas on each side of the keel give convenient access for servicing by astronauts in the EVA mode. The support arm also may be used to carry a dexterous manipulator for teleoperated or robotic servicing activities.



Evolution of servicing capabilities will call for enclosing the service bay with a hangar for crew safety and comfort and to improve working conditions. In particular, the enclosure will

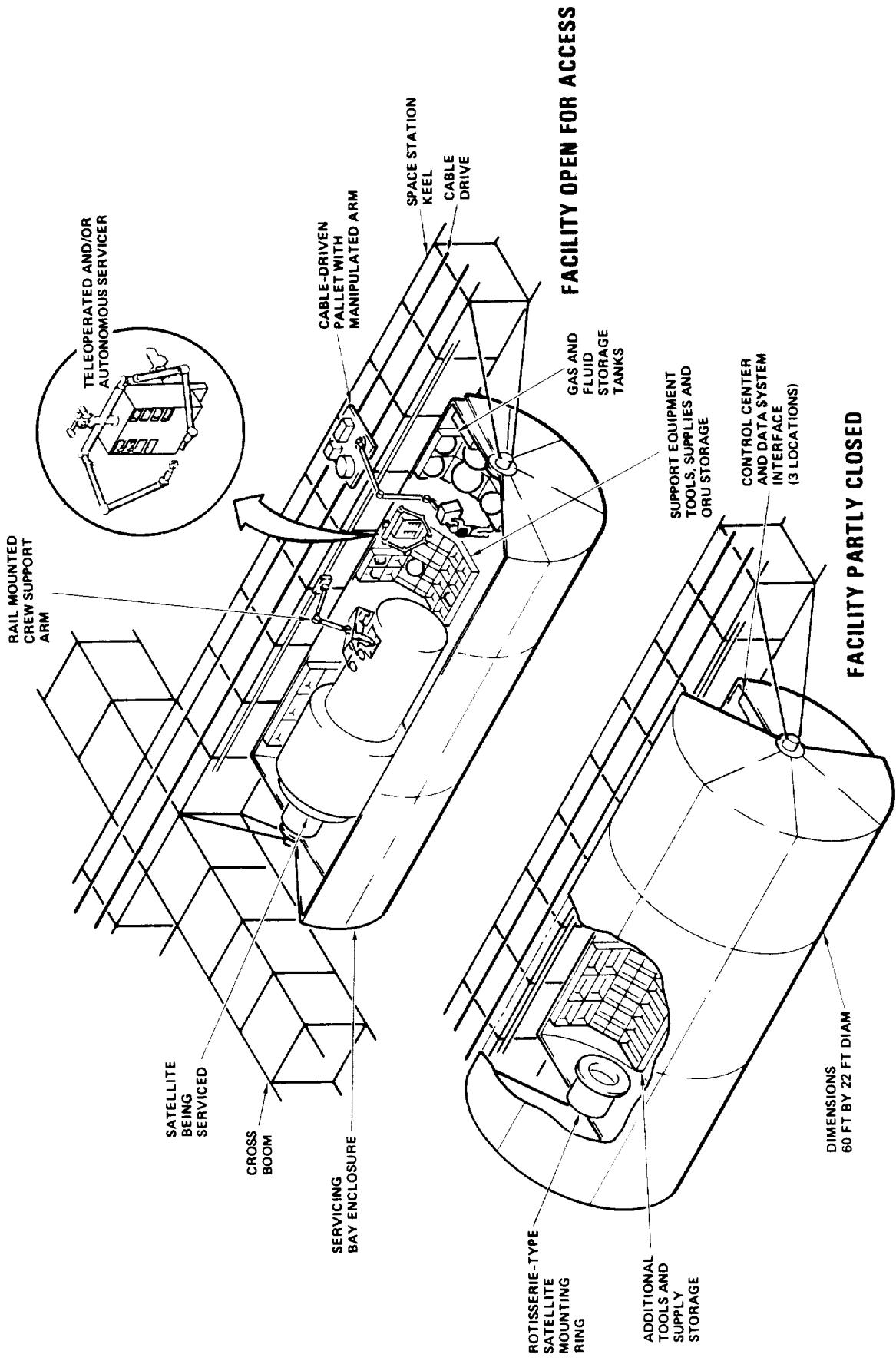
- provide thermal protection in daylight and darkness
- provide micrometeoroid protection
- shield the work area against glare by day and facilitate uniform illumination at night
- help prevent loss of equipment that may not be fastened securely
- provide convenient storage space for parts, tools, equipment and supplies.

Retractability of at least part of the service bay enclosure is required for unobstructed entry/removal of satellites and full RMS access. Several alternative enclosure concepts were considered including cylindrical shapes with clam shell doors, with a retractable half shell, or with telescoping sections.

Referring to the service bay placement along the SS keel structure, the retractable half shell configuration illustrated in the chart is best suited for access by the RMS or cable-driven transfer system, and for compatibility with the rail-mounted crew support arm concept. The wall of the fixed section provides ample storage space, easily reached by the movable manipulator(s) and the crew support arm. As in the cylindrical hanger concept developed by Martin Marietta, a rotisserie-type satellite holding fixture is envisioned to permit reorienting the satellite for easy access from all sides. A dexterous manipulator for teleoperated or robotic application is used within the facility, having access to any part of the satellite being serviced by being attached to the RMS or the movable crew support arm.

Unresolved issues in this design include questions of size and expandability, handling of bulky satellite configurations (e.g., satellites with deployed appendages) and the possibility of future conversion of the hangar into a workshop suitable for pressurization.

ENCLOSED SERVICE BAY CONCEPT



FACILITY PARTLY CLOSED

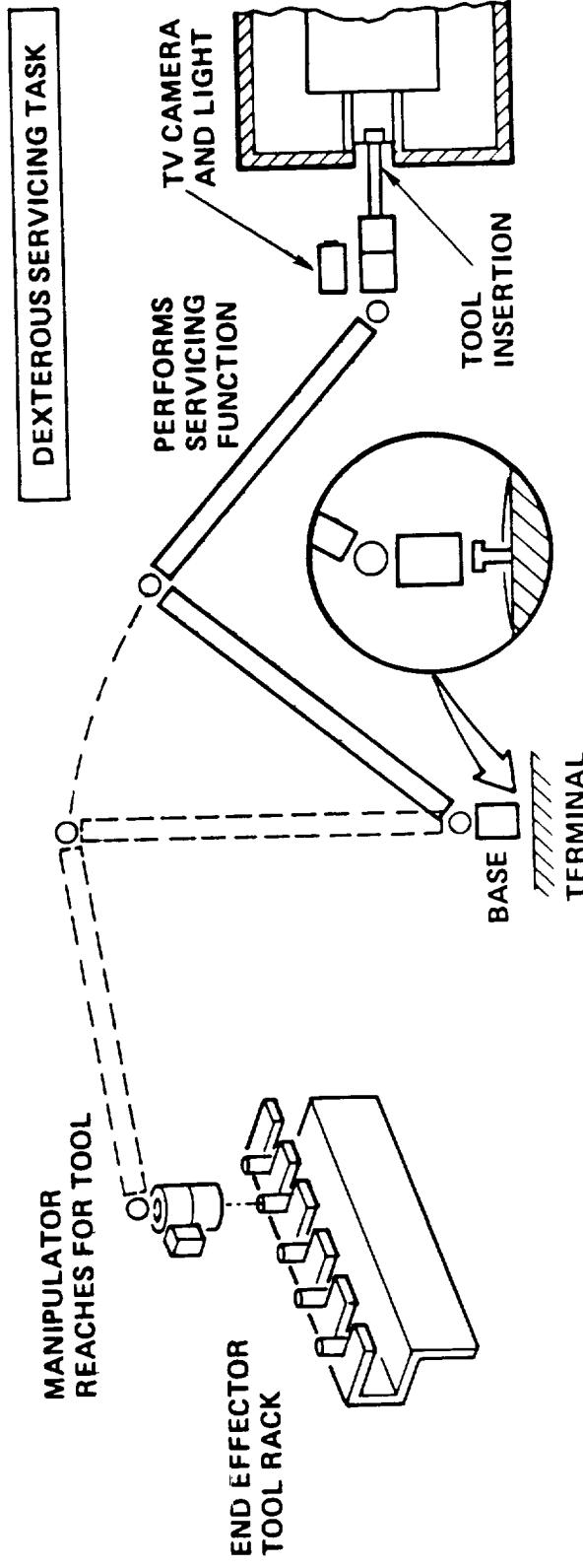
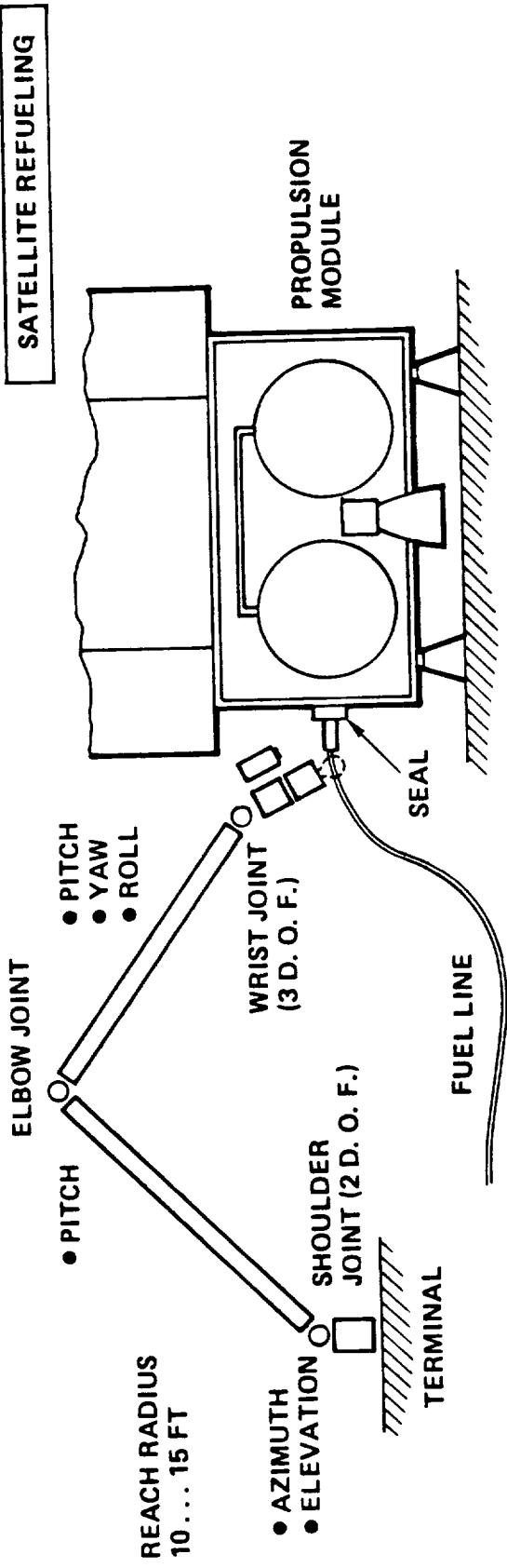
PORTABLE DEXTEROUS MANIPULATOR CONCEPT

Development of dexterous manipulators is a top priority for most servicing functions that initially would be performed by hands-on crew operation. The manipulator arm conceivably will have similar articulation as the standard large Shuttle remote manipulator system (RMS), but will only be 1/3 or 1/5 of its size for higher precision, easier control and operation in confined areas. Special end effectors will be the main element in providing greater dexterity. In principle this manipulator will be operational in the man-controlled or robotic mode.

The chart shows two examples of manipulator use, satellite refueling and dexterous tool handling. Automatic changeout of end effectors or tools may be performed comparable to current industrial robot practice.

The manipulator should be designed for portability such that it can be connected to terminals in various locations on the Space Station which provide power and control signals.

PORTABLE DEXTEROUS MANIPULATOR CONCEPT



ON-ORBIT FLUID RESUPPLY TECHNOLOGY ISSUES

On-orbit replenishment of consumables such as fluids and gases will be an important task of many service missions. Propellant transfer was first demonstrated on a recent Shuttle mission. However, with the quantity and diversity of fluids and gases used the required transfer technology still will require much development.

The chart lists general fluid resupply issues (left hand column). Automation technology concerns are listed in the right hand column.

We have studied the required technology development of handling, gauging, managing, and thermally controlling fluid transfer and storage with particular attention to operational safety. The latter includes leak detection and incipient malfunction diagnostics of pressure vessels, fluid lines and critical components.

The issue is of particular concern with regard to direct hands-on crew involvement vs. automatic or teleoperated handling. Technology evolution will replace the EVA time consuming practice of insertion and removal of fuel lines by remote operation.



GENERAL TECHNOLOGY

- LONG-TERM MATERIALS COMPATIBILITY
- EQUIPMENT LIFE: PRESSURE VESSELS,
FLUID LINES, FITTINGS, COMPONENTS
- FLUID MANAGEMENT IN ZERO-g
- MULTI-LAYER INSULATION TECHNIQUES
- HANDLING, THERMAL CONTROL, STORAGE
AND MANAGEMENT OF CRYOGENS (SEE
NEXT CHART)
- FLUID QUANTITY GAUGING
- RECHARGING HIGH PRESSURE GAS AND
VENTING

AUTOMATION-RELATED TECHNOLOGY

- HAND-ON VS. REMOTE OPERATIONS
- ORBITAL REPLACEMENT, MODULARITY
(COMPONENTS, TANKS)
- OPERATING PROCEDURES AND HAZARD
AVOIDANCE
- ALIGNING, COUPLING/DECOPPLING QUICK
DISCONNECTS
- VALVE LOCATION AND OPERATION
- LEAK DETECTION, INCIPIENT MALFUNCTION
DIAGNOSTICS (PRESSURE VESSELS, LINES
CRITICAL COMPONENTS)
- HANDLING SAFETY
 - MONOPROPELLANTS
 - BIOPROPELLANTS (HYPERGOLIC)
 - CRYOGENIC FLUIDS

PRESSURIZED MOBILE WORK STATION CONCEPT

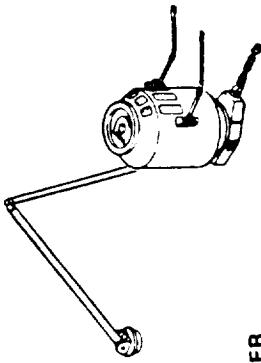
A pressurized, enclosed cherry picker equipped with manipulator arms, based on concepts developed by Grumman, will be a useful adjunct to the crew support equipment used in the servicing facility. This hybrid EVA/IVA concept permits servicing with direct crew involvement, on location, through teleoperation or robotic capability. A crew member operating inside the pressurized enclosure would be protected against EVA hazards and is less subject to fatigue when working in an EMU suit. Extended crew engagements for more than the typical 6-hour EVA sorties are possible. For mobility, the unit may be attached to the RMS arm, it could be rail or cable-mounted, or it may operate as a free flyer.

PRESSURIZED MOBILE WORK STATION CONCEPT

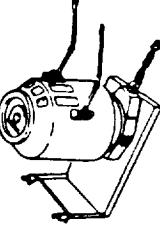


- INITIAL DESIGN STUDIES BY GRUMMAN AND OTHERS
- HYBRID EVA/IVA CONCEPT
- EASY ACCESS TO DATA SYSTEM SUPPORT
- FLEXIBLE DEPLOYMENT
- EMPHASIS ON DIRECT CREW INVOLVEMENT AND TELEOPERATION:
 - DIRECT VISUAL INSPECTION
 - CLOSE-RANGE TELEOPERATION
 - EXTENDED CREW ENGAGEMENT POSSIBLE
 - LESS FATIGUE
 - LESS CREW EXPOSURE TO POTENTIAL EVA HAZARDS
- MODIFIED USE (WITHOUT CREW) AS TELEOPERATOR OR SMART ROBOT

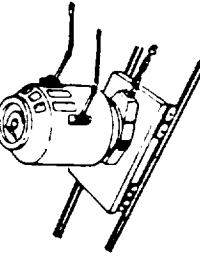
CLOSED CHERRY PICKER



MANNED FREE-FLYER



RAILED WORK STATION



TETHERED SPACECRAFT HOLDING CONCEPT

A tether of 500 to 1000 ft. length extending from the upper end of the Space Station can be used to provide a remote berthing port at times when other berthing space on the Space Station proper would be too limited or constrained. It would permit servicing a space platform in the deployed configuration in close SS vicinity without requiring station keeping maneuvers. SS resources including power, support equipment and supplies can be utilized, and hands-on crew support is available as backup option, if necessary. Teleoperation will be unhampered by transmission time delay. Capture of incoming satellites can be aided by lateral thrusters contained in a small propulsion module at the end of the tether.

Since the gravity gradient effect at small distances is minute, a 50,000 lb_m platform at 1,000 ft. distance would exert only 5 lb_f of tether tension. The tether would have to be a thin, braided line to keep from coiling when it is unreeled. Librations of the tether-mass system will be unavoidable but can be damped automatically by tether length manipulation.

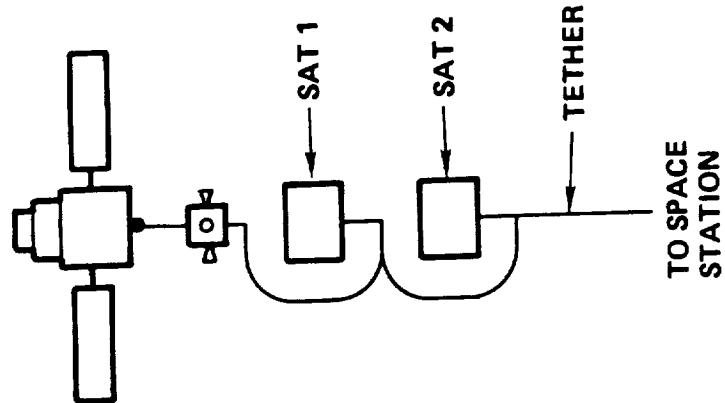
The technology of tethered payload deployment to distances several orders of magnitude greater (e.g., 60 N.M.) currently under development for scientific measurements in the upper atmosphere should be directly adaptable to this application.

Deploying the tether in upward rather than downward direction avoids obstruction of the Shuttle rendezvous approach path from below.

TETHERED SPACECRAFT HOLDING CONCEPT



TETHER WITH MULTIPLE
PARKING PORTS



TETHERED LARGE
SATELLITE

GRAPPLING DEVICE

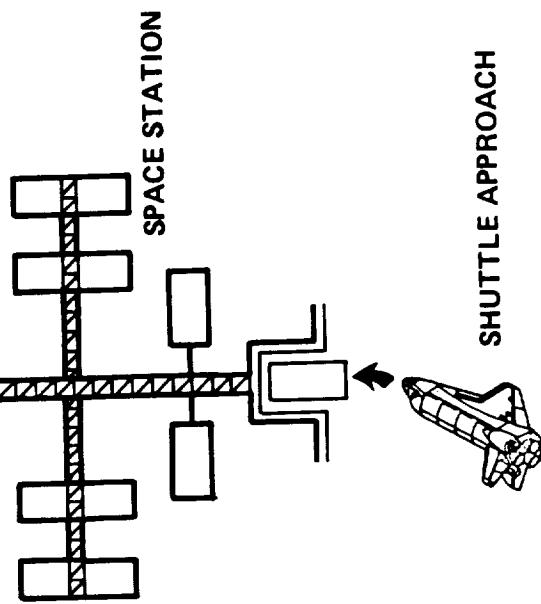
ENCLOSED CHERRY PICKER
OR ROBOTIC SERVICER MOVES
ALONG TETHER

DEPLOYED TETHER LINE,
STEM OR ASTROMAST
(100 - 300 M LENGTH)

- TRANSVERSE
PROPELLION
- STEERS TETHER FOR
HOOKUP
- PROVIDES LIBRATION
DAMPING

SPACE STATION

SHUTTLE APPROACH



The large number and diversity of communication links being utilized by the Space Station, often in connection with servicing missions, is illustrated in this chart. Of particular interest are the alternatives of performing teleoperated servicing tasks by RF command and video feedback to the human operator either via relay satellite or via direct link between the Space Station and the satellite being serviced.

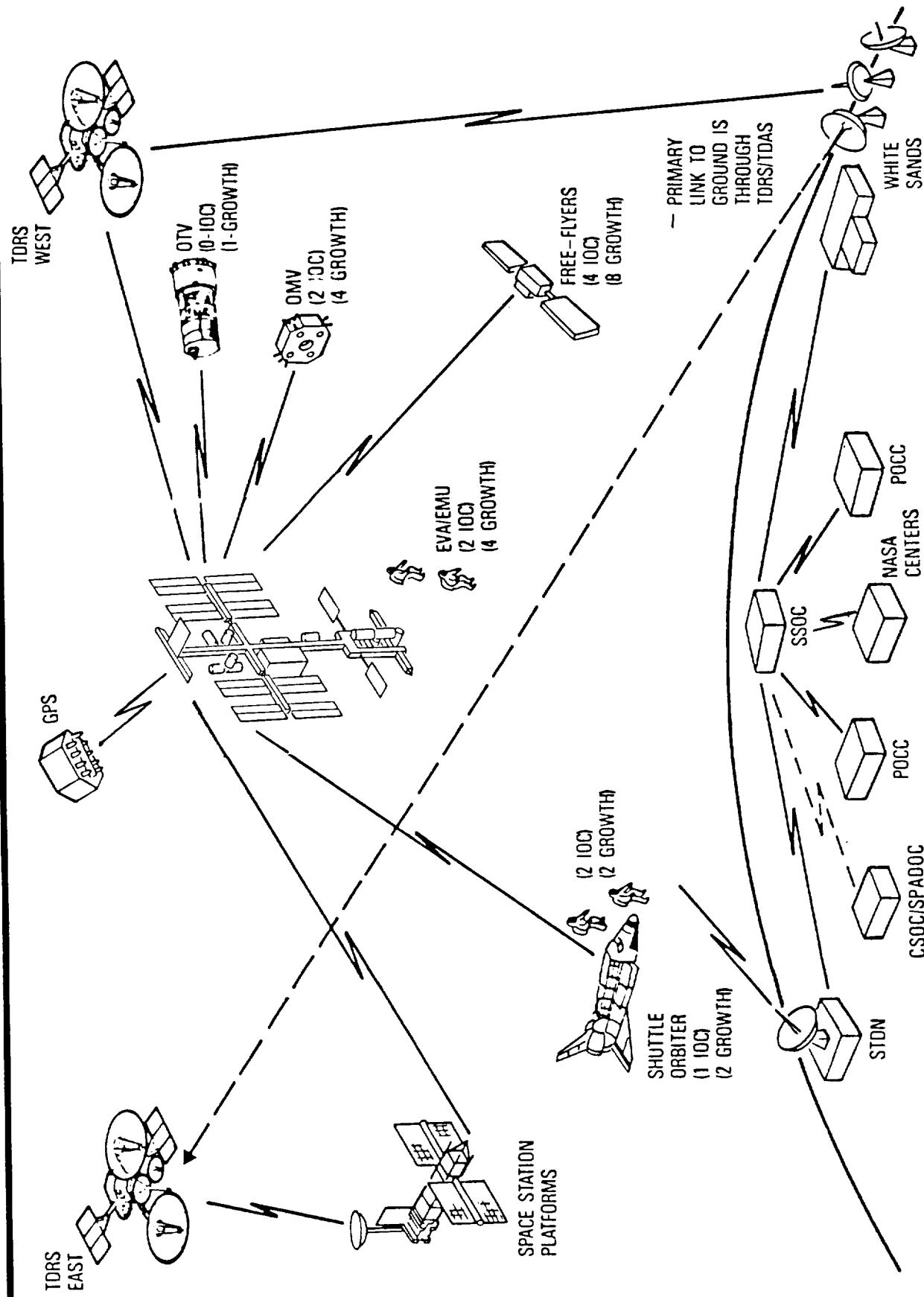
The relay link using TDRS communication may involve as many as 8 or 16 communication paths to and from geosynchronous altitude to implement the feedback control loop. It therefore may impose time delays of 5 to 10 seconds duration, including the delay caused by signal processing. This is compatible with close control of delicate teleoperation tasks. The mission would instead favor the use of fully robotic operation monitored by the Space Station crew.

The alternative of communicating via direct link greatly reduces the feedback delay and therefore is more compatible with teleoperation. It would be favored for tasks which a fully robotic servicer is unable to perform. A drawback of direct link communication is the intermittency of line-of-sight visibility of the target satellite from the Space Station. However, the mission can be planned to make best use of the total visibility "windows" lasting typically 4 to 10 hours depending on differential altitude.

Reference Mission 4 requires control of remote servicing at GEO altitude. Here the contact periods for direct communication from the Space Station are less than an hour, interrupted by about 35 to 40 minutes of non-contact, for every Space Station orbital revolution. A preferred operating mode would be control from a ground station, a departure from the guideline requiring Space Station operational autonomy.

In general, the nature and diversity of communication traffic will make heavy demands on Space Station data system support in planning and execution. In the concurrent TRW study of the Space Station data system architecture, these questions are of primary concern.

SPACE STATION COMMUNICATION TRAFFIC

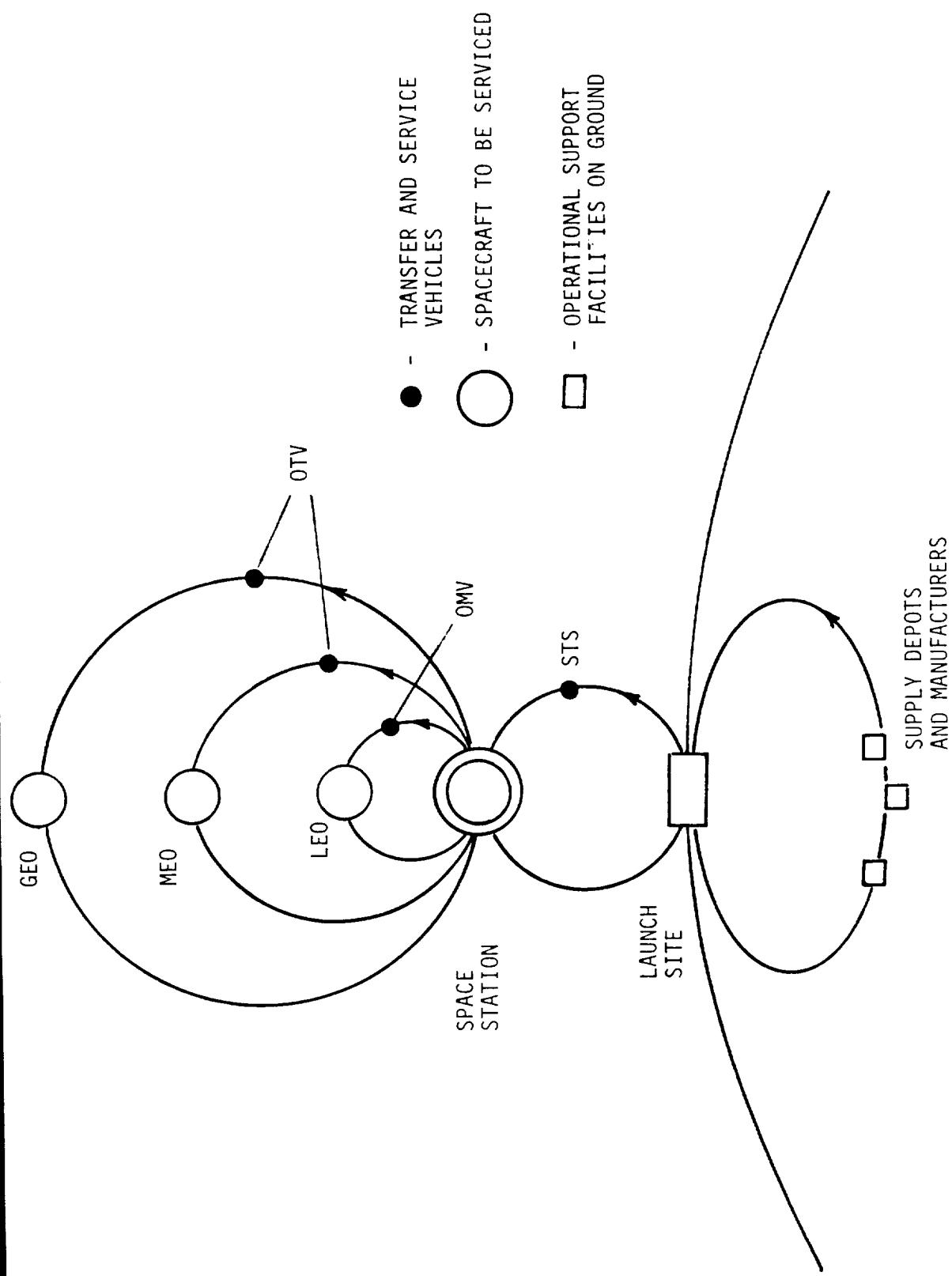


SERVICING ACTIVITY AND LOGISTICS FLOW

The chart schematically illustrates the various activity flow paths being used to implement on-board and remote servicing missions. Ascent and descent trajectories of the Shuttle, the OMV, and the OTV, including the rendezvous and berthing of these vehicles with the Space Station or the target satellite must be appropriately planned, timed, and controlled.

On the ground the logistics flow involves transport of supplies and equipment to and from the launch site. All of these activities must be fully coordinated and executed primarily on board the Space Station and demand massive support by the Space Station data system.

Trajectory planning and traffic control especially in Space Station proximity involve issues of optimization (elapsed time, fuel expenditure, guidance complexity) and mission safety. Planning and execution also must take other traffic into account to assure safety, considering other vehicles operating in the vicinity of the Space Station in a formation-flying mode but not directly involved with the servicing and logistics traffic.





3. AUTOMATED SERVICING TECHNOLOGY PRIORITIES AND EVOLUTION

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Page 28

The chart relates growth in servicing capabilities to the evolution of automation technology. Three major stages of expansion in servicing capability, in the mid '80s, the early '90s and the late '90s, are depicted.

The first stage is limited to Shuttle-based servicing, having been initiated with the repair of the Solar Max Mission spacecraft (SMM) in April 1984 on Shuttle Flight 41C. In addition to actual servicing tasks, the Shuttle also will perform early Technology Development Missions (TDMs).

The second stage starting in 1992 on the early Space Station includes more numerous and more complex servicing missions plus advanced TDMs.

During the third stage, starting in the late 1990s, servicing tasks on or near the Space Station will be performed in a routine manner, repair task complexity will further increase and even geostationary servicing missions may be performed provided the OTV is available with the requisite payload delivery and return capability.

Levels of automation advance from early manual/augmented manual and teleoperation modes through early and advanced robotic modes to near-autonomous modes. The latter incorporate machine intelligence support in diagnostics, troubleshooting, fault isolation and correction, and some levels of decision making.

The earliest milestones in servicing were achieved in three 1984 Shuttle missions, i.e., repair of the SMM spacecraft, fluid transfer demonstration, and retrieval of two communication satellites for repair/refurbishment on the ground. Manual, augmented manual and teleoperation modes were employed with the Shuttle data system providing significant support functions.

As in these pioneering missions any future evolution of servicing technology will require initial phases with men playing a key role in demonstrating and verifying new capabilities.

ROAD MAP FOR SERVICING TECHNOLOGY GROWTH

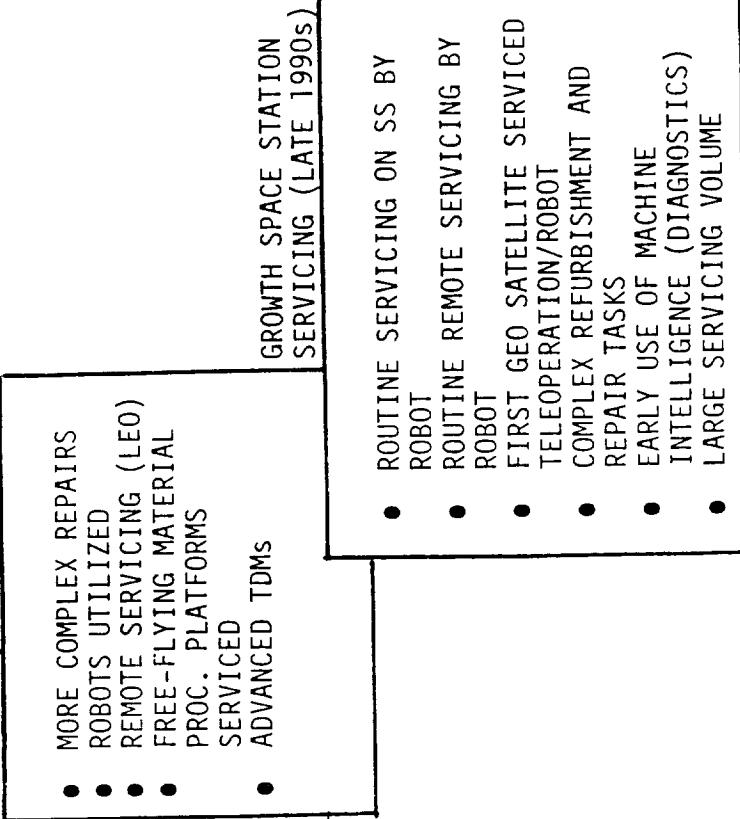
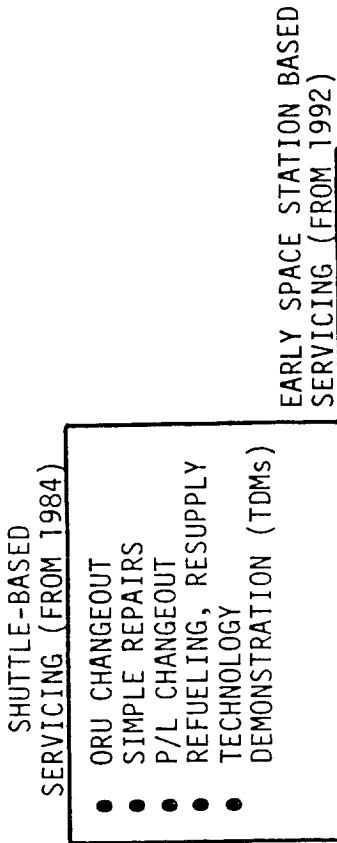
AUTOMATION LEVEL

- MANUAL
- AUGMENTED MANUAL
- ① ● TELEOPERATION
- DATA SYSTEM SUPPORT

- ABOVE PLUS
- ADVANCED
- ② ● TELEOPERATION
- EARLY ROBOTICS

- ABOVE PLUS
- ADVANCED ROBOTICS
- ③ ● EARLY EXPERT SYSTEM SUPPORT
- NEAR-AUTONOMOUS OPERATION

SERVICING FUNCTIONS

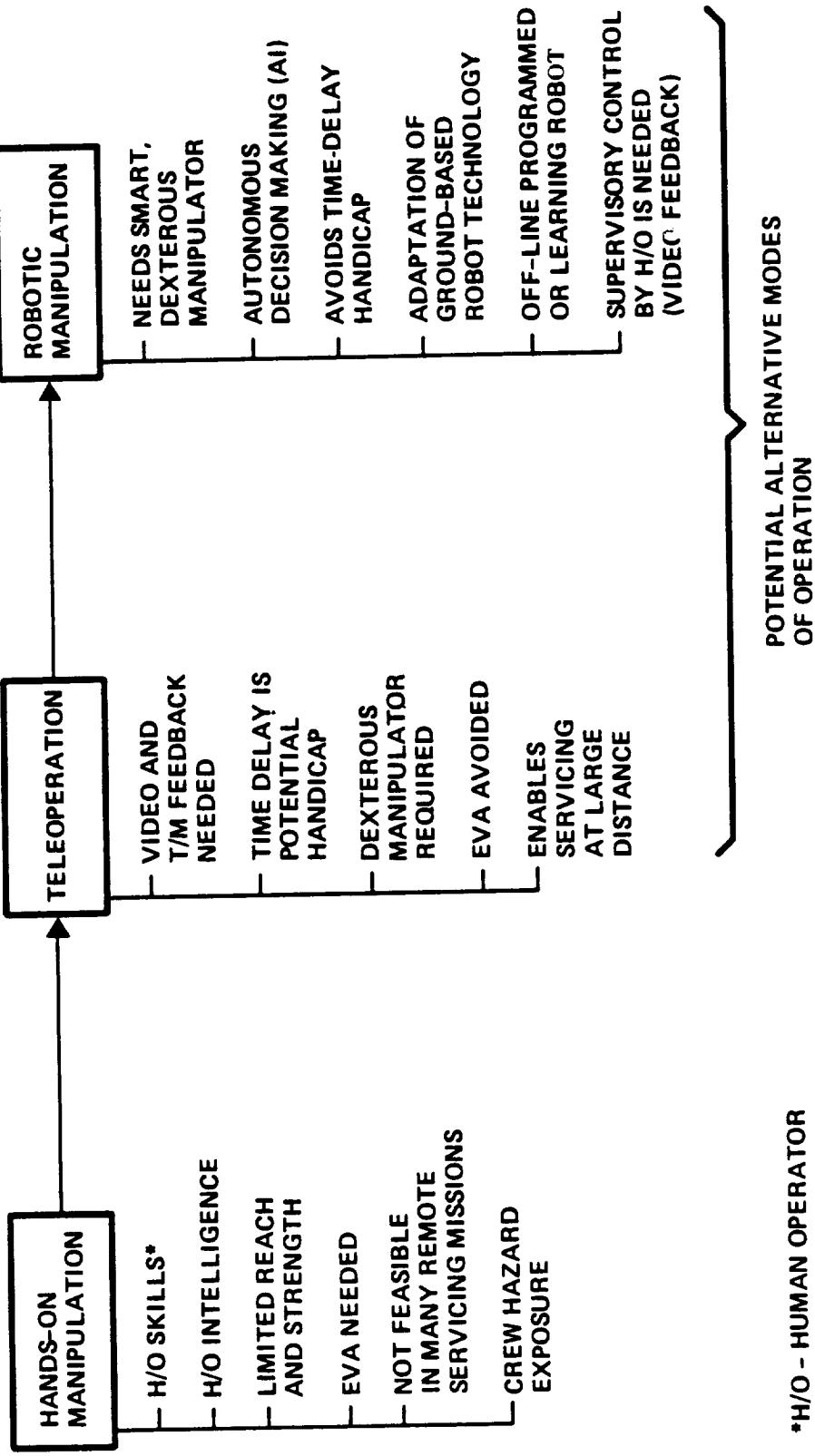


EVOLUTION OF MANIPULATION MODES IN SATELLITE SERVICING

The evolution process outlined in the preceding chart is further illustrated by the attributes and characteristics, listed on the facing page, of three levels of manipulation used in satellite servicing. The chart shows the projected evolution from hands-on to teleoperated servicing and finally to robotic servicing methods and implementation. Teleoperation, which uses the human operator's sensing, cognitive and decision making abilities, may in many instances be the best approach, particularly for servicing functions that involve unforeseen task elements and require impromptu responses. On the other hand, evolution to fully automatic operation by robot will be required to enable servicing missions where remote control by teleoperation would entail excessive feedback signal transmission time delays, e.g., those to geostationary satellites.

The common element in teleoperation and robotic servicing is the (dexterous) manipulator controlled either by the human operator or by computer signals. Robotic operation may include some degree of machine intelligence to adapt the control action to changing conditions recognized by visual or tactile sensors.

For maximum flexibility of servicing, the manipulator will be designed for utilization in either the teleoperated or robotic mode. An example is the servicer or "smart front end" to be used in conjunction with the Orbital Maneuvering Vehicle (OMV). With teleoperation available as back-up option to fully robotic action, the probability of successfully completing a difficult remote servicing task is greatly enhanced.



*H/O - HUMAN OPERATOR

SERVICING TECHNOLOGY GROWTH WITH SPACE STATION GROWTH

The chart lists the growth of generic servicing capabilities anticipated with the growth of the Space Station and advances in automation technology. On the right, specific technology advances are outlined that will support the growth in servicing requirements.

We anticipate a steady increase in servicing demands along with the Space Station evolution for reasons such as:

- More satellites in orbit that are designed for servicing
- Repeated servicing calls by satellites that were previously serviced
- Increased user confidence in successful servicing

The servicing technology evolution thus will not only reduce crew tasks and enhance crew productivity, but will also lead to greater servicing capacity of the Station, i.e., services performed per unit time, without calling for rapid expansion of space and available resources.



A. GENERIC CAPABILITY GROWTH

- FASTER SERVICING OPERATIONS
- INCREASED SERVICING CAPACITY (SPACE AND RESOURCES)
- ADVANCED TECHNOLOGY:
 - MORE ROBOTICS, LESS TELEOPERATION
 - LESS CREW INVOLVEMENT IN EACH TASK
- GREATER EMPHASIS ON AUTONOMOUS IN-SITU SERVICING (E.G., GEO)
 - GROWTH SUPPORTED BY "SCARS" AND "HOOKS" IN IOC SPACE STATION DESIGN

B. SPECIFIC TECHNOLOGY ADVANCES

- REFINED MANIPULATORS AND TELEOPERATORS
 - GREATER DEXTERITY
 - MORE TELESSENSING, TOUCH SENSORS
 - STEREO-VISION
- ADVANCED ROBOTIC SERVICING
 - SMART FRONT END FOR OMV, OTV
 - ROBOT VISION
- INCREASED USE OF MACHINE INTELLIGENCE
 - DIAGNOSTICS AND TROUBLESHOOTING
 - AUTOMATED TEST, CHECKOUT
 - MISSION PLANNING
 - LOGISTICS PLANNING AND CONTROL
- INCREASED DATA SYSTEM SUPPORT TO CREW AND AUTOMATED OPERATIONS
 - AUTOMATED TRAFFIC CONTROL AND PROXIMITY OPERATIONS INCL. RENDEZVOUS/BERTHING
 - AUTOMATED LOAD HANDLING AND TRANSFER

SERVICING TECHNOLOGY DRIVERS

The following four charts summarize Space Station operating conditions and requirements related to servicing objectives that will become "drivers" for servicing technology development.

Items listed on the left are elements that characterize, in each case, the conditions that call for technology advancement and/or other approaches to meeting growing demands on the Space Station.

Items listed on the right are principal implications relating to Space Station design and operation and specifically, to servicing technology and its evolution. Data System support is a key issue among most of the implications and growth issues identified. This support may take the form of increased data processing, data storage and retrieval, and computational activity or advanced machine intelligence for tasks such as planning, sequencing, troubleshooting, problem solving and handling of emergencies.



1. TRAFFIC FLOW ON BOARD SPACE STATION

ITEMS

- STS CARGO
- SUPPORT EQUIPMENT, TOOLS AND SUPPLIES
- MANIPULATORS, ROBOTS
- SATELLITES
- SUBSYSTEMS, ORUS, PAYLOADS
- OMV AND OTV
- CREW AND CREW SUPPORT



IMPLICATIONS/GROWTH ISSUES

- FAST TRANSFER SYSTEM, AUTOMATED
- DATA SYSTEM SUPPORT (FLOW MONITORING/
CONTROL, LOGISTICS SUPPORT, SEQUENCING)

- SHUTTLE VISITS
- SATELLITES RETRIEVED, DEPLOYED (INCL.
OMV, OTV TRAFFIC)
- SATELLITES FLYING IN FORMATION
- RENDEZVOUS/DOCKING EVENTS
- CREW MOVEMENT ON MMU



2. TRAFFIC FLOW NEAR SPACE STATION

- INTEGRATED TRAFFIC PLANNING, MONITORING
AND CONTROL (DATA SYSTEM)
- AUTOMATED RENDEZVOUS/DOCKING MODE
- SAFETY MEASURES (DATA SYSTEM)
- HUMAN CONTROL INTERVENTION, AS REQUIRED



3. FREQUENT REFUELING (OMV, OTV, SATELLITES)

ITEMS

- PROPELLANT DEPOT
 - STORABLE
 - CRYOGENIC
- LARGE VOLUME
- DEPOT LOCATION, ACCESS
- PROPELLANT TRANSFER, EQUIPMENT
- TANK TRANSFER, EQUIPMENT
- SHUTTLE PROPELLANT DELIVERY
- PROPELLANT LINE HANDLING
- CONTAMINATION, HAZARD AVOIDANCE



IMPLICATIONS/GROWTH ISSUES

- CREW INVOLVEMENT (EVA, IVA)
- AUTOMATED AND T/O HANDLING AND CONTROL
- SAFETY MEASURES, RESPONSE TO EMERGENCIES



4. HARDWARE HANDLING (ASSEMBLY/DISASSEMBLY, ORU REPLACEMENT, ETC)

- MANIPULATION (GROSS, DEXTEROUS)
- LOAD TRANSFER
- VISION SYSTEMS
- TOOLS, SUPPORT EQUIPMENT
- SEQUENCING
- PLANNING
- LOGISTICS

- CREW INVOLVEMENT (EVA, IVA)
- CONTROL STATION
- WORK STATION ARRANGEMENT
- SAFETY MEASURES
- DATA SYSTEM SUPPORT



5. SATELLITE REPAIR (ON STATION, IN SITU)

ITEMS

- TEST, DIAGNOSTICS, FAILURE DETECTION
- ACCESS TO SUBSYSTEMS
- TOOLS, PARTS, SUPPORT EQUIPMENT
- REPAIR MODES
 - AT WORK STATION
 - IN WORKSHOP (SHIRT-SLEEVE)
- MACHINING, ETC.



IMPLICATIONS/GROWTH ISSUES

- DEXTEROUS MANIPULATOR
- PRESSURIZED WORKSHOP
- AUTOMATED TEST EQUIPMENT
- EXPERT SYSTEM SUPPORTS DIAGNOSTICS,
FAILURE DETECTION
- GROWTH IN REPAIR CAPABILITY BEYOND MODULE
REPLACEMENT

6. LOGISTICS FLOW AND CONTROL

- INVENTORY CONTROL: TOOLS, SUPPLIES,
PARTS, FUEL, ETC.
- STS CARGO DELIVERY, FERRRYING OF CREWS
- GROUND SUPPORT IN SPACE STATION
RESUPPLY

- LOGISTICS PLANNING
- RESUPPLY SCHEDULING
- TRAFFIC CONTROL

DATA SYSTEM
SUPPORT



7. COMMUNICATION AND DATA MANAGEMENT

ITEMS

- COMM. LINK ACCESS (SS-TO-EARTH,
SS-TO-OMN/TARGET SATELLITE)
- ADEQUATE CHANNEL CAPACITY (VIDEO RETURN)
- DATA COMPRESSION, REDUCED FRAME RATES
- INTEGRATED DATA SYSTEM UTILIZATION
CONCEPTS
- HIGH LEVEL AND NATURAL LANGUAGES



IMPLICATIONS/GROWTH ISSUES

- COMPREHENSIVE DATA STORAGE, RETRIEVAL
- DISTRIBUTED DISPLAY/CONTROL ACCESS
- PLANNING AND MISSION/TASK SEQUENCING
- ARTIFICIAL INTELLIGENCE SUPPORT TO
AUTOMATED SERVICING

8. CREW INTERFACES

- CENTRAL AND SUBSIDIARY CONTROL STATIONS
- DISPLAY/CONTROL FUNCTIONS
- DATA SYSTEM ACCESS
- CREW SUPPORT EQUIPMENT
- CREW PROTECTION PROVISIONS (EVA, IVA)



- CREW TASK PLANNING,
SEQUENCING } AI SUPPORT
} EVOLUTION
- PROBLEM SOLVING
(TROUBLESHOOTING)
- MOBILE WORK STATION (ENCLOSED CHERRY
PICKER) FOR ON SITE TELEOPERATION

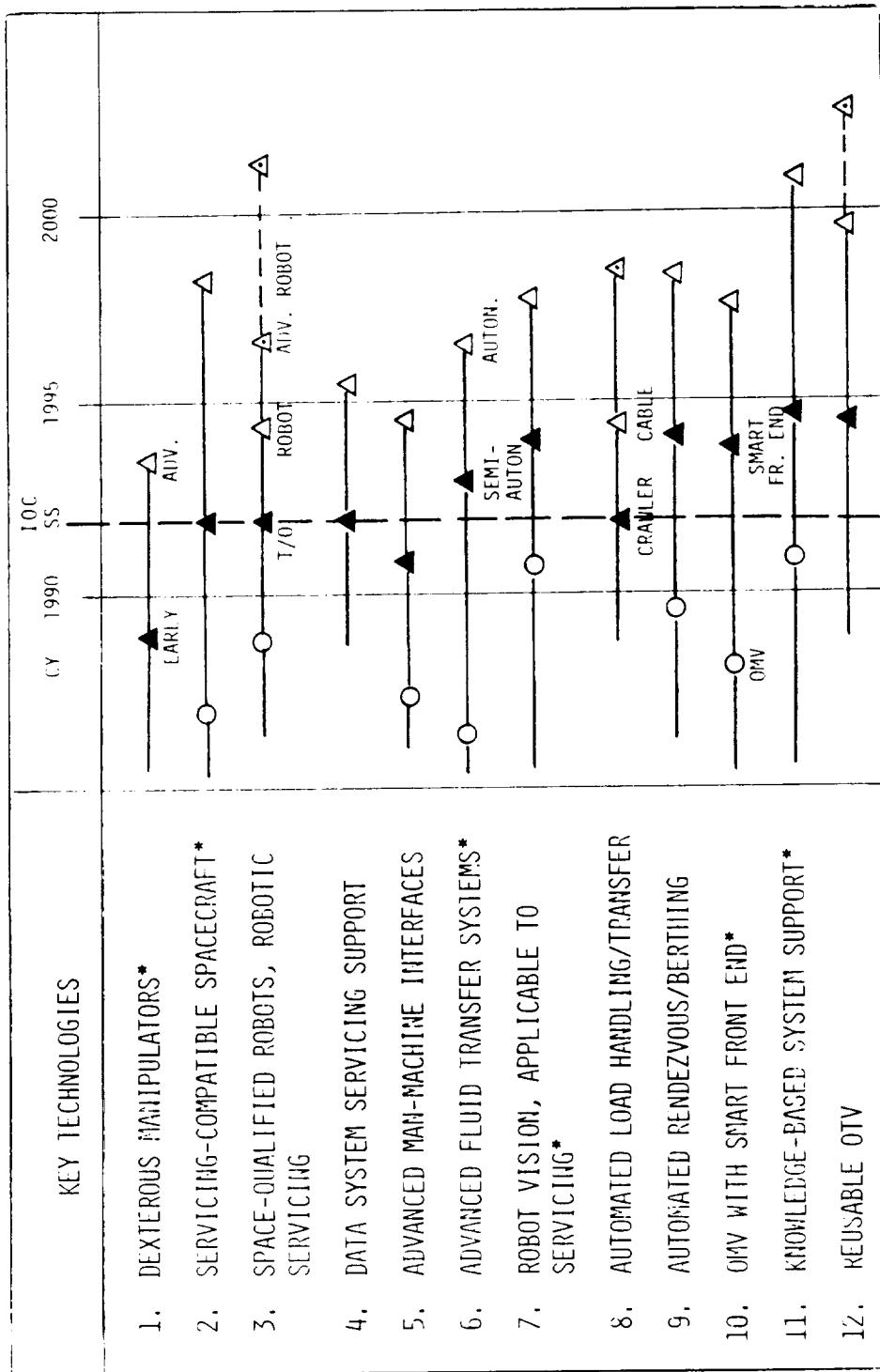
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72
100% AUTOMATIC ALARM

TECHNOLOGY DEVELOPMENT FORECAST

The chart presents a preliminary projection of key servicing automation technology evolution in the next two decades. The stages shown include technology demonstration, early and advanced automation and, in some instances, future growth capabilities. Availability of six of the key technologies listed, at least in an early stage of development, will be essential for servicing functions required at the time of initial Space Station operations (1992) or soon thereafter.

TECHNOLOGY DEVELOPMENT FORECAST



* ASSUMES MAJOR R&D FUNDING FOR SS AUTOMATION, STARTING FY 1986

○ - DEMONSTRATION ▲ - EARLY ▲ - ADVANCED ▲ - FUTURE GROWTH CAPABILITY



4. SPACECRAFT DESIGN APPROACHES FOR SERVICING

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SPACECRAFT DESIGN FEATURES FOR SATELLITE SERVICING

The chart lists principal spacecraft design features essential to enabling or facilitating satellite service. The left-hand side summarizes design features of the spacecraft bus and its subsystems, the right-hand side those of any payloads intended for on-orbit replacement.

The design of the NASA Goddard Space Flight Center developed Multi-mission Modular Space-craft (MMS) being used in the Solar Max Mission Spacecraft and Landsat embodies these requirements. Other examples are the Gamma Ray Observatory (GRO) which uses several MMS replaceable modules and the Advanced X-Ray Astrophysical Facility (AXAF) which has replaceable payload instruments and support modules. (See subsequent charts.)



<u>SPACECRAFT BASE</u>	<u>SPACECRAFT PAYLOADS</u>
<ul style="list-style-type: none">● INSIDE-OUT DESIGN FOR MAXIMUM ACCESSIBILITY● LARGE MODULAR ORBIT REPLACEMENT UNITS (ORUS)● ON-ORBIT REFUELING● ON-ORBIT REPLENISHMENT OF OTHER CONSUMABLES● STANDARD INTERFACES - PAYLOADS, CREW SUPPORT EQUIPMENT, SHUTTLE, RMS, OMV, OTV, OTHERS● SATELLITE SAFING FOR ACCESS● SUBSYSTEMS DESIGNED FOR AUTOMATIC FAULT DETECTION, ISOLATION, REPORTING, REDUNDANCY MANAGEMENT	<ul style="list-style-type: none">● DETACHABLE ON-ORBIT● DESIGNED FOR MAXIMUM ON-ORBIT SERVICING● MODULARITY FOR EXTENSION OF CAPABILITY, FLEXIBILITY OF MISSION OBJECTIVES● STANDARD INTERFACES WITH SPACECRAFT● STANDARD COLOR CODES, MARKINGS, IDENTIFICATION FOR EASE OF REPLACEMENT, MAINTENANCE AND REPAIR

AUTOMATED SERVICING DESIGN REQUIREMENTS

The following two charts summarize principal design characteristics of the Space Station, the Orbital Maneuvering and Transfer Vehicles (OMV, OTV) and satellites which enable or facilitate automated on-orbit servicing.
(The preceding chart listed only those features related to servicing, in general.)



1. SPACE STATION - PROVIDES:

- INTEGRATED AUTOMATION SUPPORT CAPABILITY BY SPACE STATION DATA SYSTEM WITH DISTRIBUTED ACCESS POINTS FOR
 - COMMANDS
 - DISPLAYS
 - SERVICING TASK SEQUENCING
 - TEST AND CHECKOUT SEQUENCES
- RMS AND TRANSFER SYSTEM TO COVER ALL SS AREAS
- DIRECT LINE-OFF-SIGHT COMMUNICATION LINK IN REMOTE SERVICING
- ADVANCED TDRSS DIRECT-LINK SS-TO-SATELLIE COMMUNICATION FOR REMOTE SERVICING
- DEXTEROUS MANIPULATOR, DISTRIBUTED PLUG-IN TERMINALS

2. OMV/OTV - PROVIDES:

- SERVICING KITS FOR TELEOPERATED OR AUTOMATED REMOTE SERVICING
- MULTIPLE TV CAMERAS AND LIGHTING
- CONVENIENT MATING INTERFACES BETWEEN OMV/OTV AND CARGO
- AUTOMATED RENDEZVOUS/DOCKING/BERTHING CAPABILITY



3. SATELLITES - PROVIDE:

- READY TELEOPERATOR ACCESS TO UNITS EXPECTED TO BE SERVICED
- CONVENIENT REMOVAL/REATTACHMENT OF THERMAL COVERS TO FACILITATE SERVICING ACCESS
- FIXED OR PORTABLE GRAPPLER FIXTURES ON REMOVABLE UNITS
- STANDARDIZED ELECTRICAL AND MECHANICAL INTERFACES ON REPLACEABLE UNITS
- STANDARDIZED FLUID INTERFACES
- REFUELING CAPABILITY
- ASSEMBLY AND DEPLOYMENT CAPABILITY FOR LARGE SATELLITES
- TELEOPERATOR ACCESS FOR DEPLOYMENT/RETRACTION, REPOSITIONING OF APPENDAGES
- EXTERNAL TERMINALS FOR DIAGNOSTICS IN SERVICING AND CHECKOUT.

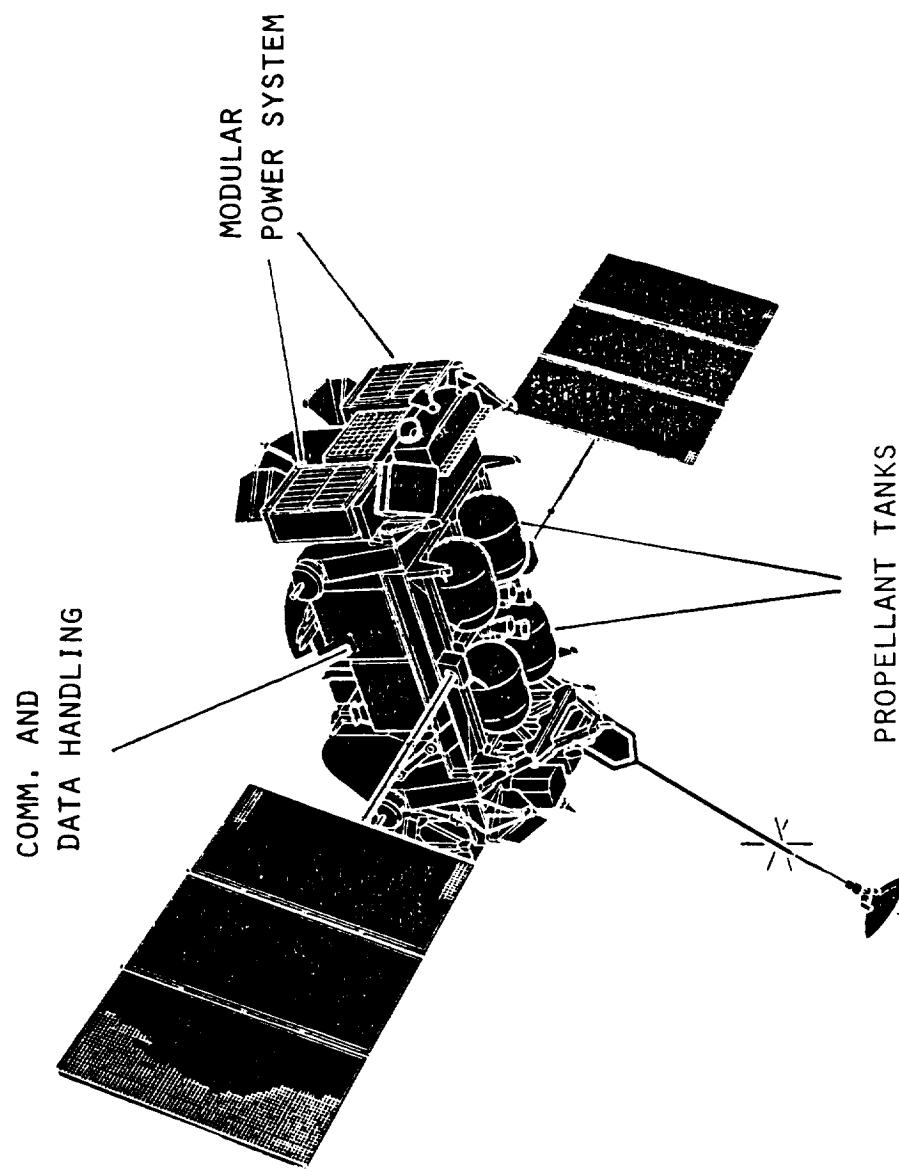
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SERVICEABLE HARDWARE ON GRO

The Gamma Ray Observatory (GRO) developed initially for Shuttle-based servicing, also may require servicing by the Space Station. (See Reference Mission No. 1.) The Orbit-Replaceable Units (ORUs) are the modular power system (2) and the command and data handling module. The propulsion subsystem is designed for on-orbit refueling. The scientific payload instruments are not intended for orbital replacement in view of the difficulty of performing such a task at an early stage of servicing technology development.

Note that the postulated Space-Station-based GRO refueling mission (discussed in Section 2) involves automated servicing tasks which may not actually be implemented during the life time of this spacecraft.

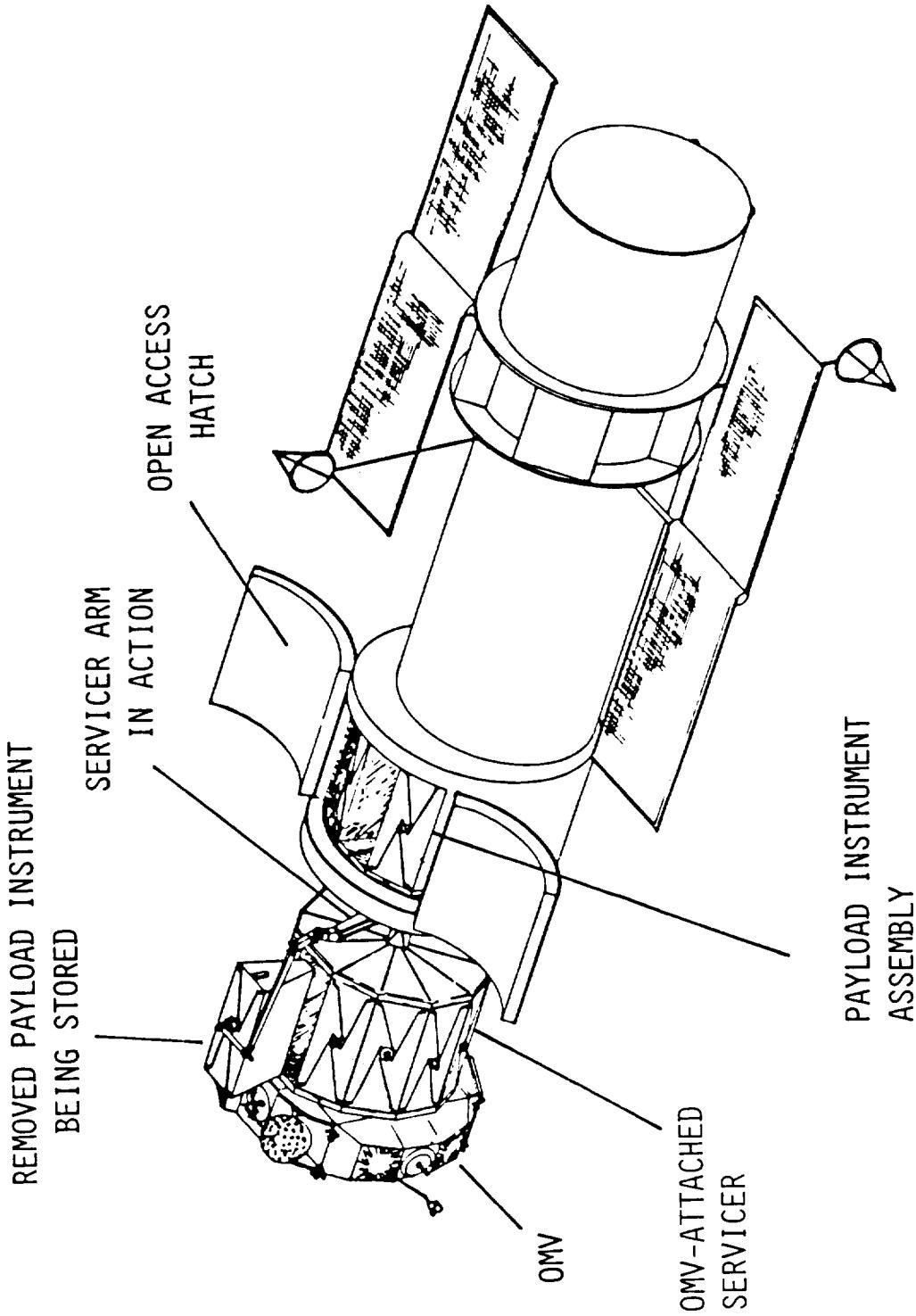
SERVICEABLE HARDWARE ON GRO



The chart shows an early concept of AXAF being serviced in the free-flying mode by an OMV equipped with a robotic servicer.

The removable payload units are focal plane instruments grouped in a cylindrical arrangement at the aft end of the observatory facility. In the design shown, payload instruments can be removed in radial (lateral) direction. To effect the changeout the servicer, berthed at the aft bulkhead, uses its manipulator arm to reach into the open access hatch, where it pulls out one instrument at a time. The instrument is shown in the process of being stored in an empty compartment of the servicer magazine. The next step for the servicer arm is to take a replacement unit from the magazine and insert it into the AXAF focal plane compartment just vacated.

AXAF servicing is similar to the instrument changeout process on the Space Telescope (HST) however, at this time, neither AXAF nor HST are actually scheduled for in situ servicing, remote from the Space Station.



SOURCE: J. TURNER, "TELEOPERATOR MANEUVERING SYSTEM", SATELLITE
SERVICING WORKSHOP, NASA/JSC, JUNE 1982

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5. AUTOMATION TECHNOLOGY TRANSFER TO EARTH BASED APPLICATIONS

This and the two subsequent charts address the potential transfer of automation technology developed for space-based servicing to ground-based applications in industrial production. Other applications may include deep mining, underwater operations, nuclear power plant emergency activities, and working near explosives i.e., operation in unsafe working environments.

The chart lists typical technology advancements currently being emphasized in manufacturing. However, the other applications listed above also will be potential users.

The development of space-based automation can benefit the industrial automation field in two ways:

- (1) It provides a strong stimulus to advancing the state-of-the-art so that at least part of the development cost supports the US terrestrial economy by promoting technology growth.
- (2) Robotic capabilities peculiar to space-based servicing needs will be developed, tested and applied operationally on the Space Station. They include the adaptability and flexibility to deal economically with "one-of-a-kind" servicing functions. Such flexibility will be much in demand in the factory of the future (see the following charts), and a direct technology spin-off potential is evident.





- COMPUTER INTEGRATED MANUFACTURING (CIM)
- ADVANCED (SMART) ROBOTS
- ADVANCED SENSING AND CONTROL TECHNOLOGY
 - VISION SYSTEM
 - TACTILE SENSORS
 - IR SENSORS
 - OBJECT IDENTIFICATION, DECISION MAKING
 - VOICE CONTROL, VOICE FEEDBACK
- SOFTWARE
 - FORMATS
 - OPERATING LANGUAGES
 - PRODUCTION CONTROL
- WORKING ROBOTS, USED TO CARRY
 - TOOLS TO MACHINES
 - MATERIAL TO MACHINES
 - FINISHED PRODUCTS TO STORAGE OR TO OTHER WORK STATIONS



- ADAPTABLE MACHINES
- REPROGRAMMABLE MACHINES (BY KEYSTROKE)
- FLEXIBLE AS OPPOSED TO FIXED AUTOMATION
- RESPONSIVENESS TO NEW SITUATIONS, ELIMINATE OBSOLESCENCE
- ECONOMIC PRODUCTION OF "QUANTITIES OF ONE"
- MIXED BATCHES
- LOW INVENTORY/ZERO INVENTORY TRENDS
- PROLIFERATION OF MODELS
- SOFTWARE LINKAGE BETWEEN DIVERSIFIED COMPUTERS

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ROBOTS FOR DIVERSIFIED SERVICING TASKS

1. ATTRIBUTES OF SPACE STATION ROBOTS THAT RELATE TO FACTORY OF THE FUTURE:
 - SPACE STATION ROBOTS DESIGNED TO HANDLE ONE-OF-A-KIND SERVICING TASKS
 - FLEXIBLE, REPROGRAMMABLE ROBOTS FOR DIVERSIFIED TASKS
 - SMART ROBOTS THAT RESPOND TO UNFORESEEN CONDITIONS
 - MOVING ROBOTS THAT TRANSFER EQUIPMENT AND SUPPLIES AS INSTRUCTED
 - SOFTWARE LINKAGE BETWEEN DISTRIBUTED COMPUTER SYSTEMS
2. ROBOTS OPERATING IN HOSTILE ENVIRONMENTS
 - APPLICABLE TO OPERATION IN DEEP MINES, UNDER WATER, THREE-MILE ISLAND, FIRE FIGHTING, ETC.



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6. CONCLUSIONS, RECOMMENDATIONS AND SUMMARY

CONCLUSIONS

Space Stations are needed to advance on-orbit satellite servicing toward a fuller, more effective and more economical utilization of spaceflight. Starting with a broadened R&D flight program and initial applications in the early 1990s, paced by servicing technology evolution, the objective is to obtain full-scale operation by 2000.

The chart outlines the role of teleoperation, robotics, artificial intelligence and data system support in relation to different mission classes and servicing functions. In-situ servicing in low, and particularly, in geostationary earth orbit becomes a principal driver toward fully automated, robotic manipulation techniques. The Space Station data system will play a key role in providing comprehensive support functions in all phases of satellite servicing.

Twelve automation technologies identified below are key to space servicing.

1. Dexterous manipulators*
2. Servicing-compatible spacecraft*
3. Space-qualified robots, robotic servicing
4. Data system servicing support
5. Advanced man-machine interfaces
6. Advanced fluid transfer systems*
7. Robot vision*
8. Automated load handling/transfer
9. Automated rendezvous/berthing
10. OMV with smart front end*
11. Knowledge-based system support*
12. Reusable OTB.

*Needed for IOC Station

Space-based servicing will draw on current developments in automation technology such as advanced robotics, expert systems, robotic vision, speech recognition, natural language, data processing and display, fault detection/recovery, computing and software. However, practical application of this technology to Space Station automation objectives requires a continuing major development effort. Spin-off benefits to terrestrial applications could be in the area of flexible/adaptable automation, for example in the economical production of small quantities, and in advanced data management and information transfer.

CONCLUSIONS

- MANY SATELLITE SERVICING FUNCTIONS BENEFIT FROM, OR RELY ON, AUTOMATION SUPPORT.
- SATELLITE SERVICING REQUIRES MORE TELEOPERATION AND LESS ROBOTICS THAN OTHER AUTOMATED SPACE STATION ACTIVITIES.
- ROBOTIC SERVICING DEVELOPMENT IS DRIVEN BY IN SITU, PARTICULARLY GEOSTATIONARY, SATELLITE SERVICING OBJECTIVES.
- IN SITU SERVICING BY TELEOPERATION FEASIBLE ONLY IF TRANSMISSION DELAYS ARE REASONABLY SMALL, I.E., 0.25 TO 1.0 SEC.
- MAJOR DATA SYSTEM SUPPORT ESSENTIAL FOR PLANNING, SCHEDULING, EXECUTION, MONITORING AND OTHER SERVICING FUNCTIONS.
- SERVICING SUPPORT BY ARTIFICIAL INTELLIGENCE WILL EXPAND WITH SS EVOLUTION.
- TWELVE KEY AUTOMATION TECHNOLOGIES WERE IDENTIFIED, SOME OF WHICH ARE NEEDED FOR SERVICING ON THE IOC SPACE STATION.
- GROUND-BASED AUTOMATION TECHNOLOGY APPLICABLE TO SATELLITE SERVICING.
- SERVICING AUTOMATION, IN TURN, WILL BENEFIT GROUND APPLICATIONS, I.E., INDUSTRIAL PRODUCTION IN SMALL QUANTITIES, AS A SPACE TECHNOLOGY SPIN-OFF.

RECOMMENDATIONS

In implementing the Space Station Program, NASA intends to advance the state-of-the art in automation and robotics:

- (a) for use in Space Station operations, and
- (b) to benefit the U.S. economy by exploiting space-based automation progress through technology spin-off to earth-based applications.

In line with these objectives, and based on our study results, we are making five major recommendations with regard to servicing and automation technology as input to the current planning for the Space Station definition phase.

- Crew safety should be the principal concern of defining conventional as well as automated servicing approaches. This requires major attention even in the earliest phases of automated servicing, planning and technology development.
- On-orbit servicing requires that the early and growth Space Stations be designed for rendering effective and economical servicing functions. It also requires that space systems to be serviced incorporate into their configurations, the ability to accept servicing with a minimum of crew effort, support equipment, down time, and cost. This two-way thrust should start as soon as possible under an integrated government (NASA and DoD) policy for designing, planning, and executing of space servicing.
- The IOC Space Station should include automated features such as: load transfer capability, integral verification and test systems, advanced data handling and information processing techniques, a master program for logistics management, appropriate fuel and fluid handling and transfer equipment, and controlled Space Station proximity operations, rendezvous and docking.
- The IOC Space Station must accommodate growth in servicing and automated systems. Provisions for early mods to the IOC Station, through hooks and scars, as well as aggressive planning for expanded resources to support servicing must be reflected in the impending Phase B study efforts and programmatic decisions.
- Key automation technology developments should start as soon as possible. An integrated plan for design, development, test, and evaluation of automation/robotic/AI devices should be formulated and implemented with adequate funding.



- CREW SAFETY IS A PRINCIPAL CRITERION IN DEFINING ALL SERVICING APPROACHES INCLUDING AUTOMATED SERVICING.
- EFFECTIVE SERVICING REQUIRES A TWO-WAY APPROACH:
 - (1) SPACE STATION DESIGNED TO PROVIDE SERVICE
 - (2) SATELLITES DESIGNED TO FACILITATE BEING SERVICEDWE NEED TO GET THE CYCLE STARTED.
- THE IOC SPACE STATION SHOULD INCLUDE AUTOMATED FEATURES SUCH AS:
 - LOAD HANDLING, TRANSFER DEVICES AND DEXTEROUS MANIPULATORS
 - BUILT-IN VERIFICATION AND TEST SYSTEMS
 - DATA SYSTEM SERVICING SUPPORT
 - LOGISTICS, SPARES, STORAGE CONTROL
 - FLUID HANDLING AND TRANSFER
 - OTHER
- PROVIDE HOOKS AND SCARS TO THE IOC SPACE STATION FOR EVOLUTIONARY GROWTH ALONG WITH PLANNED RESOURCE CAPACITY FOR EXPANDED SERVICING.
- INITIATE DEVELOPMENT OF KEY AUTOMATION TECHNOLOGIES.

SUMMARY

This chart summarizes highlights, conclusions and recommendations derived from TRW's Space Station automation study. It calls out the major benefits accruing from automated, space-based satellite servicing, indicates the potential technology spin-off to terrestrial applications in the U.S. industry, and emphasizes the need for early funding to initiate the required automation technology R&D effort.

SUMMARY

- AUTOMATION CAN EXPEDITE IOC SPACE STATION SERVICING FUNCTIONS
- TECHNOLOGY EVOLUTION WILL GREATLY EXPAND SERVICING CAPABILITIES
- ORBITAL SERVICING (SATELLITES AND SPACE STATION ITSELF) IS A PRINCIPAL DRIVER OF AUTOMATION TECHNOLOGY DEVELOPMENT
- AUTOMATION ENABLES IN SITU SERVICING MISSIONS
- ASSIGN PRIORITIES TO KEY AUTOMATION TECHNOLOGY DEVELOPMENT AND EARLY SHUTTLE DEMONSTRATIONS
- EARLY FUNDING IS NEEDED TO INITIATE SPACE STATION AUTOMATION R&D
- SOME SPACE SERVICING AUTOMATION TECHNOLOGIES ARE POTENTIALLY TRANSFERABLE TO GROUND
- "FACTORY OF THE FUTURE" APPLICATIONS.







